Army Research Laboratory

Viewgraph Supplement to the Proceedings of the First Army Research Laboratory Acousto-Optic Tunable Filter Workshop

by Neelam Gupta

ARL-SR-54-S

March 1997

Approved for public release; distribution unlimited.

Army Research Laboratory
Adelphi, MD 20783-1197

ARL-SR-54-S **March 1997**

Viewgraph Supplement to the Proceedings of the First Army Research Laboratory Acousto-Optic Tunable Filter Workshop

Neelam Gupta, Editor
Sensors and Electron Devices Directorate, ARL

Abstract

Acoustic-optic tunable-filter (AOTF technology is a recent development that offers potential for rapid, frequency-agile tuning over a large optical wavelength range. An AOTF is an electronically tunable phase grating set up in an anisotropic crystal by the propagation of an ultrasonic wave in the crystal. Such filters have many attractive features, such as small size, lightweight, computer controlled operation, large optical wavelength range of operation, and no moving parts; and their operation can be made ultrasensitive by the use of advanced signal processing algorithms. These filters are being used in many applications such as the design of new spectroscopic instruments, remote detection and monitoring of chemicals, optical communication networks, tuning of laser cavities, etc.

Foreword

This volume, *Supplement to the Proceedings of the First Army Research Laboratory AOTF Workshop*, contains the viewgraphs that were presented at the conference.

Acousto-optic tunable filter technology (AOTF) has made significant progress in the last 30 years. These electronically tunable filters are finding many applications in various fields, such as chemical and environmental sensing, communications, hyperspectral imaging, pharmaceuticals, medicine, semiconductor processing, space exploration, etc. Due to their compact size and no moving parts, AOTF's offer numerous advantages over traditional grating-based technology. There is a tremendous potential offered by this technology, which remains to be fully utilized. One of the main motivations in organizing this workshop, the first of its kind, was to create a forum of experts and users that would provide the synergy to give a much needed impetus for the rapid development and exploitation of this promising technology.

In the Fall of 1995, I had the great privilege of visiting many Russian institutions involved in the research and development of this technology, and meeting with Russian scientists working in this field. This experience gave me the idea to bring U.S. and Russian scientists together for an intimate exchange of information and ideas for the advancement of AOTF technology. This workshop provided an avenue to implement this idea.

It has been a great deal of work to pull this workshop together, but the outcome has been worth many times the effort. It was a great experience to listen to the experts as well as the newcomers talk about AOTF basic research and applications for two full days.

I would like to thank my sponsors at the Army Materiel Command (AMC) and Army Research Laboratory (ARL) for providing the necessary funds to make this workshop possible. I would also like to thank every attendee for participating in this workshop, especially the Russian scientists for taking this long trip.

Neelam Gupta
Army Research Laboratory
Adelphi, MD, USA

Contents

First ARL Workshop on Acousto-Optic Tunable Filter Technology

Center for Adult Education, University of Maryland, College Park, MD

Tuesday, September 24, 1996
AOTF Technology

Morning Session, Chair Andree Filipov, USARL-SEDD

8:30 - 8:55	Check-in/Registration/Continental Breakfast
8:55 - 9:00	Administrative Announcements
9:00 - 9:20	Welcome & ARL Overview, John Pellegrino, Director, Sensors and Electron Devices Directorate, US Army Research Laboratory
9:20 - 9:40	AOTF Overview, Neelam Gupta, USARL
9:40 - 10:10	Progress in AOTF Technology, I. C. Chang, Aurora Associates, Santa Clara, CA
10:10 - 10:40	Break
10:40 - 11:10	Collinear AOTF Spectrometers: Problems, Results, Methods of Spectral Measurements, V. I. Pustovoit, Central Bureau of Unique Instrumentation, Moscow, Russia, and N. Gupta, USARL
11:10 - 11:40	Recent Advances in AOTF Design and Fabrication at SPSAAI, V. V. Kludzin, S. V. Kulakov, and V. V. Molotok, St. Petersburg State Academy of Aerospace Instrumentation, St. Petersburg, Russia
11:40 - 1:00	Lunch

Afternoon Session, Chair Neelam Gupta, USARL-SEDD

1:00 - 1:30	Application of AO Interaction for Filteration of Arbitrary Polarized Radiation,V. Voloshinov, Physics Department, Moscow State University, Moscow, Russia
1:30 - 2:00	Improvement of Resolution of Visible AOTF in TeO_2, V. Pelekhaty, Brimrose Corp. Of America, Baltimore, MD
2:00 - 2:30	Growth of Acousto-optic Crystals with High Anisotropy and Development of Multichannel Acousto-optical Processors, Y. B. Pisarevsky

2:30 - 3:00	Break
3:00 - 3:30	Progress in AOTF Technology for WDM Systems, D. Smith, Case Western Reserve University, Cleveland, OH
3:30 - 4:00	Integrated AOTF for Blue-Green Spectral Region, C. S. Tsai and A, M. Matteo, University of California, Irvine, CA
4:00 - 5:00	AOTF Demonstrations
6:30	Banquet, University Of Maryland, College Park

Wednesday, September 25, 1996
AOTF Applications

Morning Session, Chair Andrzej Miziolek, USARL-WMRD

8:30 - 9:00	Registration/Continental Breakfast
9:00 - 9:30	Application of AOTF in Analytical Chemistry, C. D. Tran, Marquette University, Milwaukee, WI
9:30 - 10:00	Application of AOTF Technology for Chem/Bio Detection, N. Gupta and N. F. Fell Jr., US Army Research Laboratory, Adelphi, MD
10:00 - 10:30	Break
10:30 - 11:00	An AOTF-Based Near-Infrared Spectrometer for Process Control, S. Medlin, U. Eschenaur, and W. Danley, Brimrose Corp. Of America, Baltimore MD
11:00 - 11:30	Application of AOTF to Near IR Spectroscopy and High Fidelity Spectroscopic Imaging, E. N.Lewis, National Institutes of Health, Bethesda, MD
11:30 - 1:00	Lunch

Afternoon Session, Chair James Gillespie, USARL-ISTD

1:00 - 1:30	Factors Affecting AOTF Image Quality, L. J. Denes, B. Kaminsky, M. Gottlieb, and P. Metes, Carnegie Mellon Research Institute, Pittsburg, PA

1:30 - 2:00	An AOTF Camera for Multispectral Imaging, S. Simizu, R. T. Obermyer, C. J. Thong, M. Uschak, S. G. Sankar, Advanced Materials Corp., Pittsburg, PA, D. J. Denes, D. A. Purta, and M. Gottlieb, Carnegie Mellon Research Institute, Pittsburgh, PA
2:00 - 2:30	Simultaneous Multispectral Imaging with a 12 Parallel Channel Tunable Camera, J. A. Carter III, D. R. Pepe, Photonics Systems, Inc., Melbourne, FL, and M. L. Shah, MVM Electronics, Inc., Melbourne, FL
2:30 - 3:00	Break
3:00 - 3:30	Polarimetric Hyperspectral Imaging Systems, L.-J. Cheng, G. Reyes, and C. La Baw, Jet Propulsion Laboratory, CA, and G. P. Li, University of California, Irvine, CA
3:30 - 4:00	Multiplexing Methods in AOTF Multispectral Imaging, P. Treado, and J. Turner, University of Pittsburgh, Pittsburgh, PA
4:00 - 4:30	Remote Spectral Imaging System Based on an AOTF, T. Vo-Dinh, Oak Rigde National Laboratory, Oak Ridge, TN
4:30	Workshop Closing

AOTF TECHNOLOGY: A BRIEF OVERVIEW

Dr. Neelam Gupta

Sensors & Electron Devices Directorate
Army Research Lab
Adelphi, MD 20783

FIRST ARL WORKSHOP ON AOTF TECHNOLOGY
24-25 September 1996

Center for Adult Education, University of Maryland

INTRODUCTION

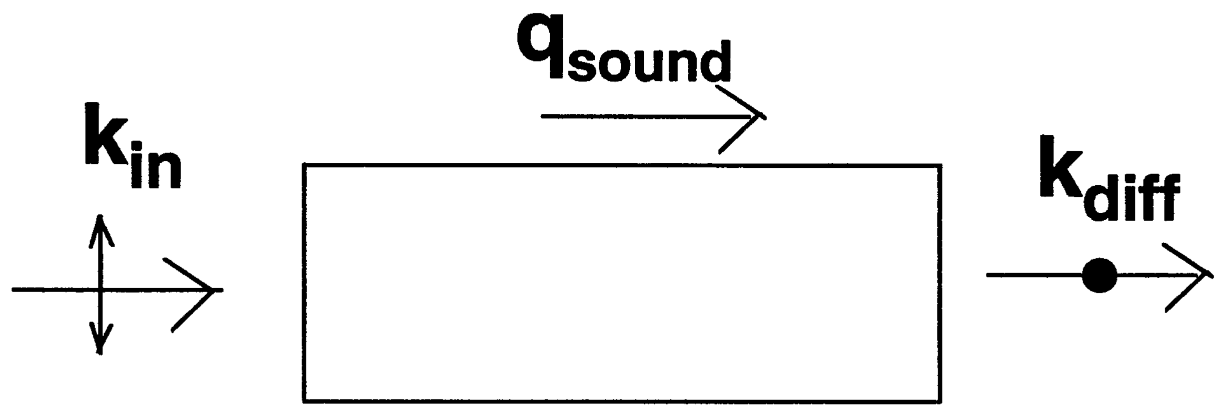
What is an AOTF:

A moving diffraction grating is set up in an anisotropic crystal, when an acoustic beam propagates through it as a result of an applied rf field. When light is incident on this grating, it is diffracted with polarization orthogonal to the incident beam for only a specific incident wavelength as a result of the acousto-optic interaction. The wavelength can be tuned by varying the rf frequency, forming an electrically tunable optical filter. Such an optical filter is called an Acousto-Optic Tunable Filter (AOTF).

Collinear AOTF: Incident light, sound and diffracted light beams all propagate in the same direction.

Noncollinear AOTF: Incident light, sound and diffracted light beams do not propagate in the same direction.

COLLINEAR AOTF

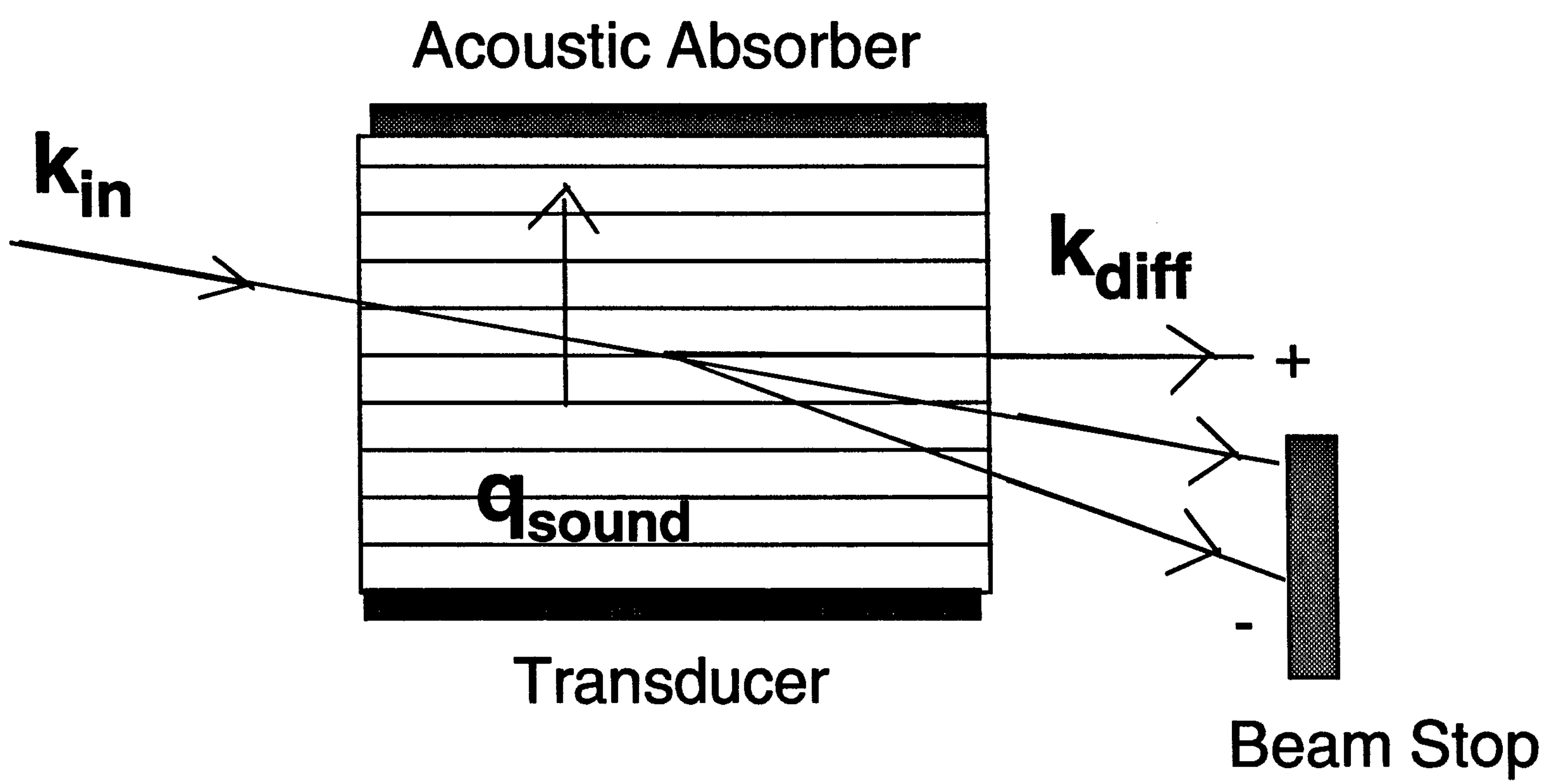


$$k_{diff} = k_{in} + q$$

$$\lambda = (n_o - n_e) v_s / \Omega$$

Spectral Resolution $\Delta\lambda/\lambda = \lambda/L\Delta n$

NONCOLLINEAR AOTF



AOTF MILESTONES

•1922	Brillouin	Theoretical Prediction of AO Interaction
•1932	Debye, et al.	Experimental Demonstration of AO Interaction
•1955	Rosenthal	Theoretical Discussion of Color Control by Ultrasound Grating
•1967	Dixon	Acoustic Diffraction of light in Anisotropic Media
•1969	Harris, et al.	Collinear AOTF
•1968	Arlts, et al.	Synthesis of TeO_2
•1971	Nieh et al.	Analysis of Collinear AOTF
•1973	Kusters, et al.	Optimization for AOTF
•1974	Chang	Noncollinear AOTF in TeO_2
•1977	Ohmachi, et al.	Integrated Optic AOTF
•1987	Pustovoit, et al.	Okean Satellite Trasser Apparatus

AOTF ADVANTAGES

- Lightweight, Compact, Portable
- No Moving Parts, Rugged
- Reliable
- Reproducible Operation
- Rapid Tuning and Scanning
- Low Drive Power
- All Solid State Operation
- High Spectral Resolution
- Polarization Separation
- Broad Tuning Range
- Wide FOV
- High Throughput
- Sequential or Random λ Access
- Capability for Multi λ Operation
- High Signal-to-Noise Ratio
- Uncooled Operation
- Programmable, Computer Control
- Arbitrary Spectral Signal Generation

AOTF APPLICATIONS

- Sensing of Chemical & Biological Agents: Fluorescence, Absorption, emission, Raman, LIBS, etc.
- Remote Sensing/ Environmental Monitoring
- Multispectral and Hyperspectral Imaging
- Medical Applications; i.e. Cancer Detection
- Tuning of Laser Wavelength
- Process and Quality Control
- Astronomical Observations
- Communication; i.e. WDM

AOTF APPLICATIONS (Continued)

- Polarization Spectroscopy
- Fire Sensing
- Water Quality Monitoring on Space Station
- Spectroscopy on Comet Lander
- Spectroscopy on Mars Lander
- Cassini Mission to Saturn
- Others ???????
- Under water Spectroscopy

KEY ELEMENTS IN AOTF SYSTEM DESIGN

- Material Selection
- Crystal Geometry
- Transducer Design
- AOTF Cell Architecture
- Electronics
- Computer Interface
- Processing Software

Spectral Coverage/Materials

Spectral Bands Covered (µm)	Material	Type
0.4 - 4.5	$LiNbO_3$	Collinear
0.25 - 0.8	Xtal Quartz	Collinear
0.2 -0.7	MgF_2	Collinear
0.4 - 4.5	$CaMoO_4$	Collinear
0.35- 4.5	TeO_2	Noncollinear
1.1 - 17	$T\ I_3AsSe_3$	Collinear or Noncollinear
0.35 -20	Hg_2Cl_2	Noncollinear

KEY PLAYERS IN AOTF TECHNOLGY

- **US Govt:** ARL, ERDEC, JPL, NASA, NIH, ORNL, etc.
- **US Univ:** Case Western Univ, Marquette Univ. WI, UC Irvine, Univ. of Pittsburg, etc.
- **US Companies:** ATT Labs, Aurora Assoc, Advanced Materials Corp., Brimrose Corp. of America, Carnegie Mellon Research Institute, Neos, Photonics Systems, etc.
- **Russia:** CBUI, Inst. of Xtallography, SPAAI, MSU, etc.
- **Others:** Matsushita Electronics, Japan; France, U.K.

AOTF TECHNOLOGY STATUS/CHALLENGES

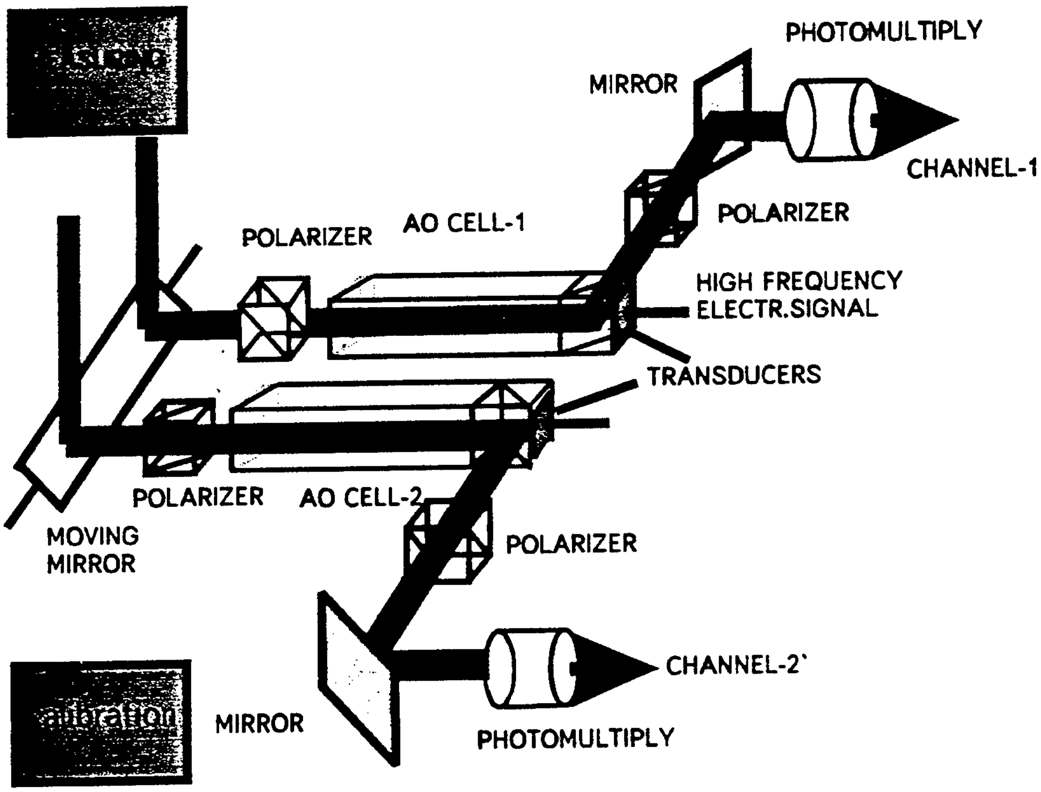
- Very Promising Technolgy
- Much Progress in Visible/NIR
- Labor Intensive Fabrication
- Improvement of Existing Material, i.e. TeO_2
- Development of New Materials for UV/ Long IR
- Novel designs, i.e. Implement Backward Diffraction
- Reduce Cost
- Automate Fabrication
- Find New Applications

Collinear AOTF Spectrometers: Problems, Results, and Methods of Measurements

by

V. I. Pustovoit, Central Bureau of Unique Instrumentation of Russian Academy of Sciences, Russia; &
N. Gupta, Army Research Laboratory, USA

OPTICAL SCHEME OF AO SPECTROMETERS



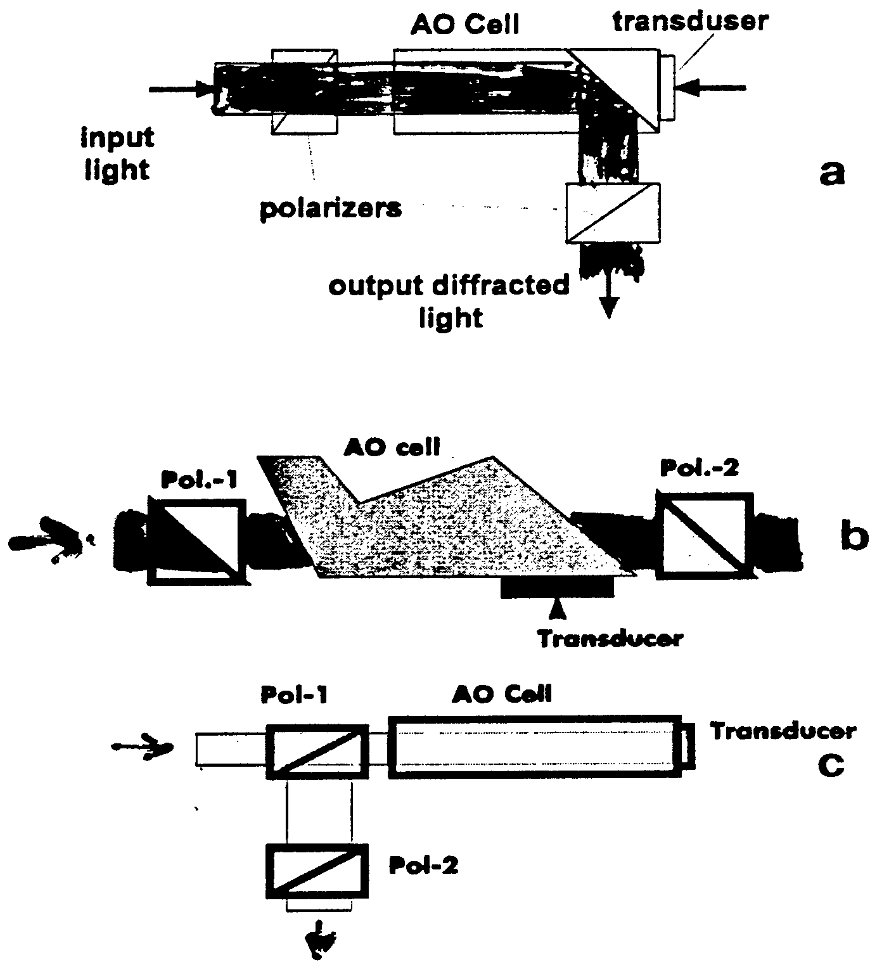
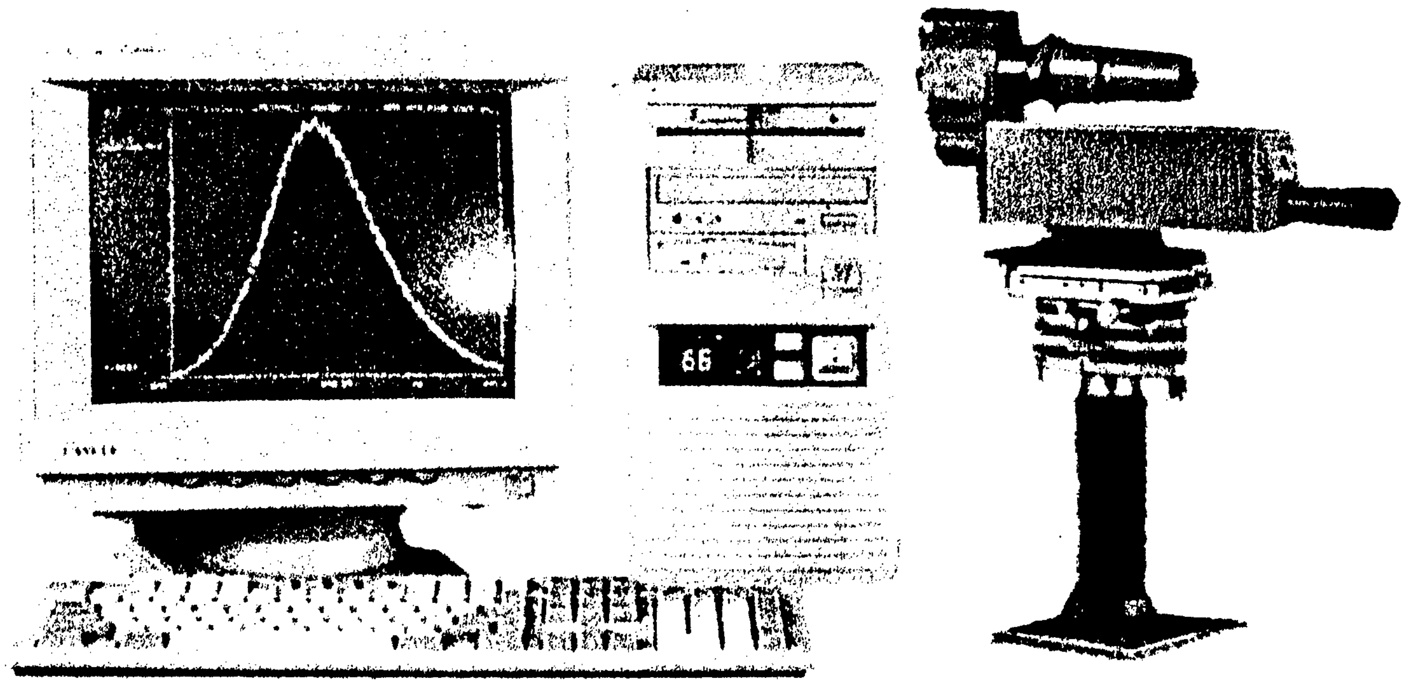


Fig.2. Collinear Acousto-Optic Filters:
a- with mirror inside of crystal,
b- with reflecting sound wave surface,
c-with reflecting diffracted light..

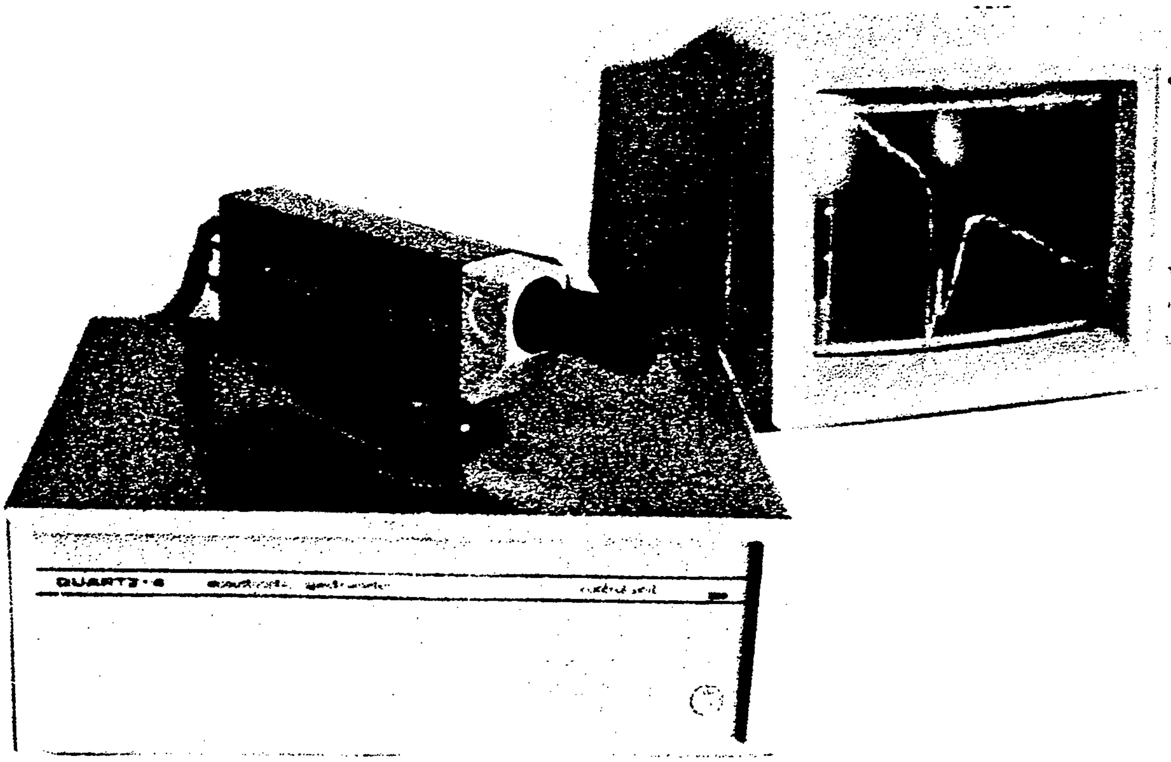

ФОТОГОЛОВКА
СПЕКТРОМЕТР КВАРЦ


AO Spectrometer
for airborne and surface-based
platforms
POLAS-128



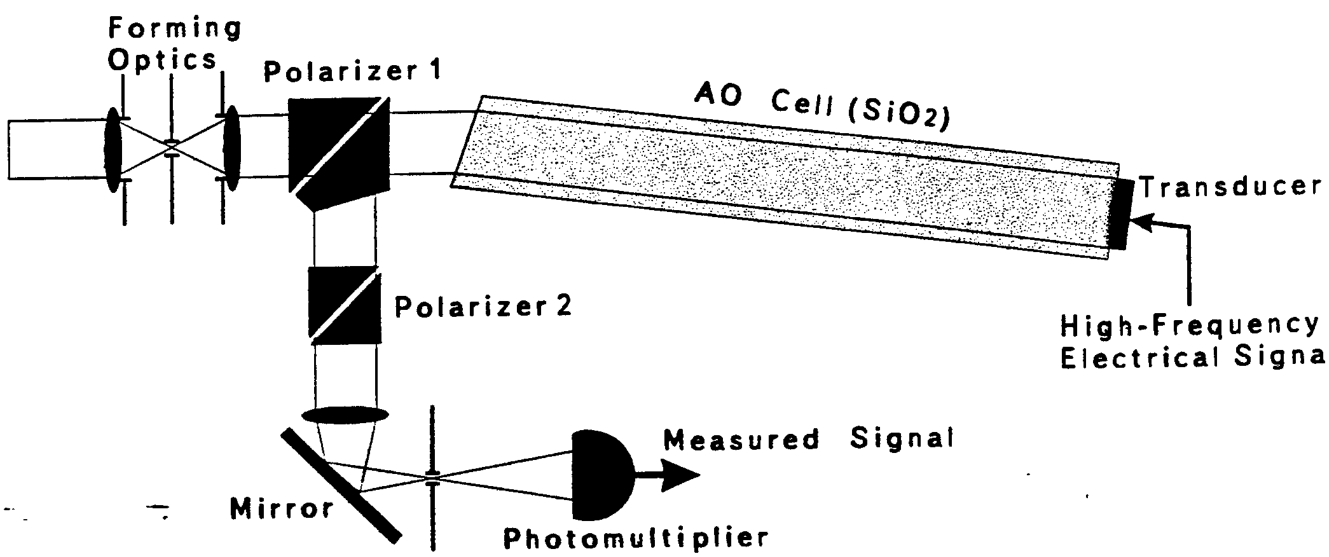
Acousto-optical Spectrometer of visible and UV bands

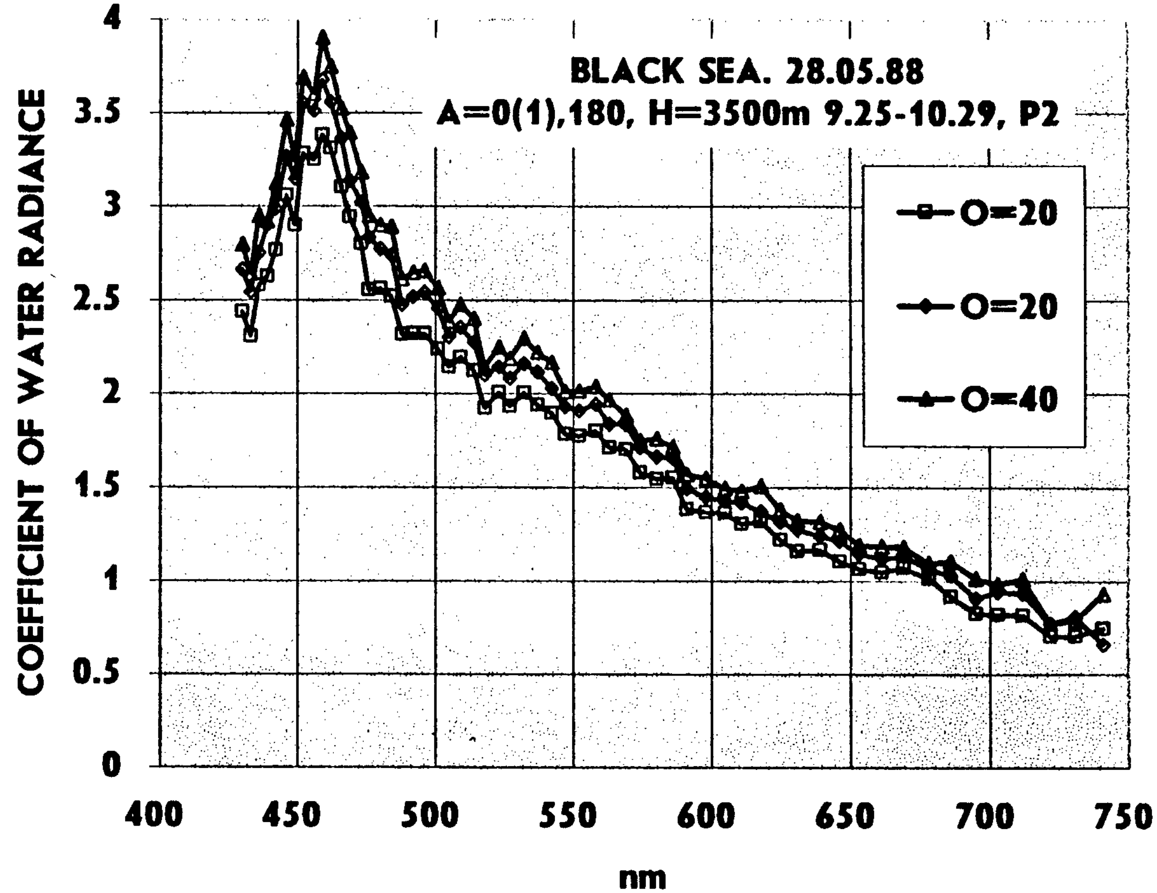
Acousto-Optic Spectrometer Quartz-4

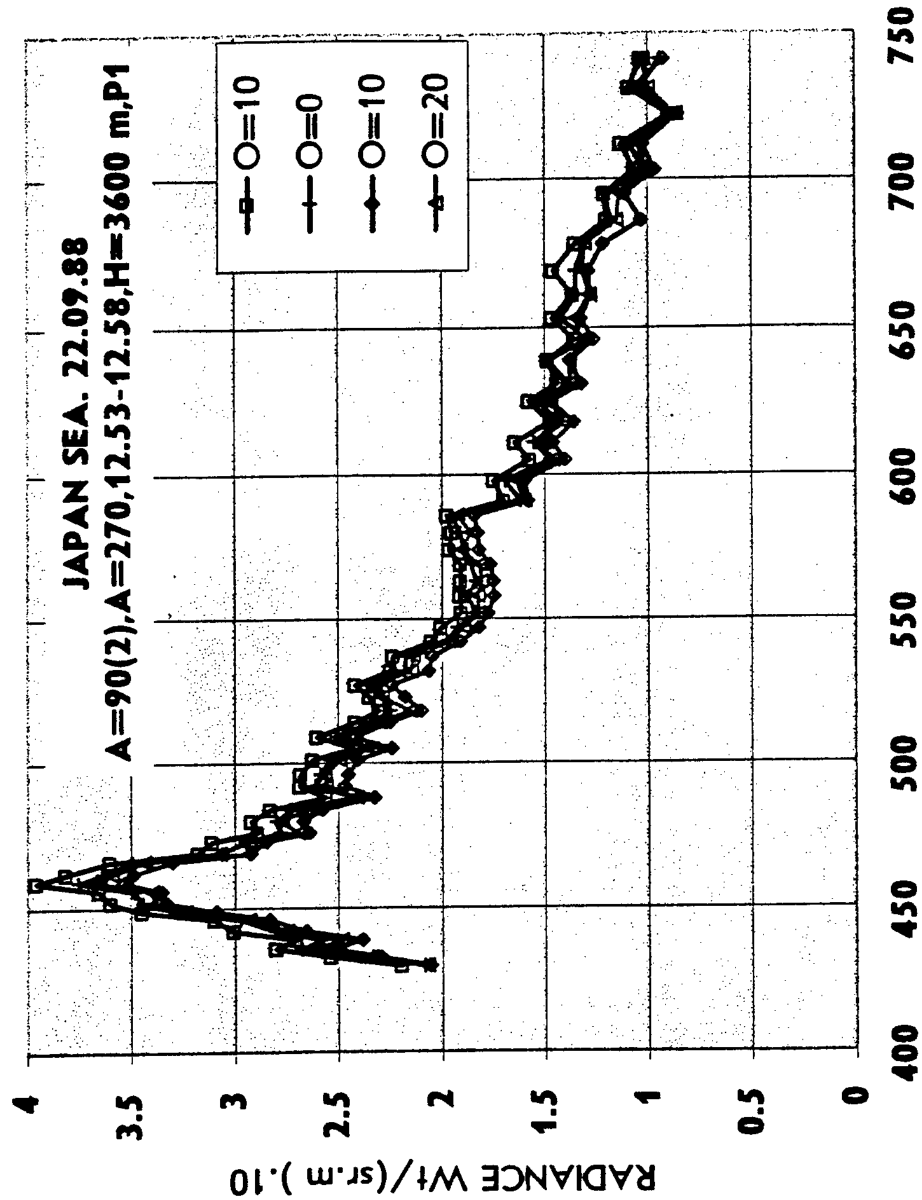


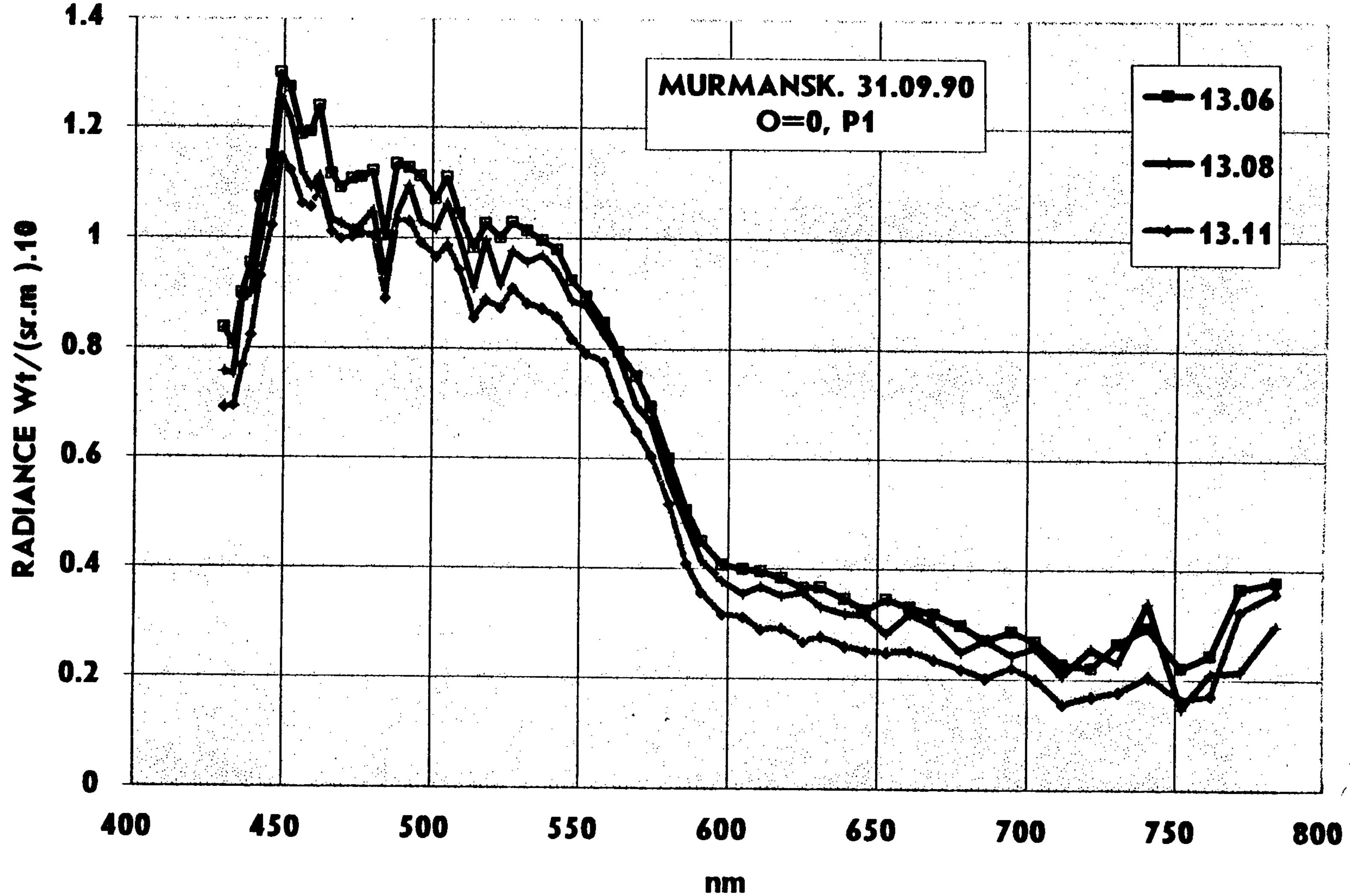
Specifications:

Spectral Range, nm	415 to 790
Resolution, nm	0.10 to 0.25
Wavelength measurement instrumental error, nm	± 0.15
Sensitivity, W	10-12
Dynamic range, dB	45
Minimum measurement time at one spectral point, ms	32
Max. number of spectral points	4096
Input angle	2 degrees
Input window	ϕ 6 mm

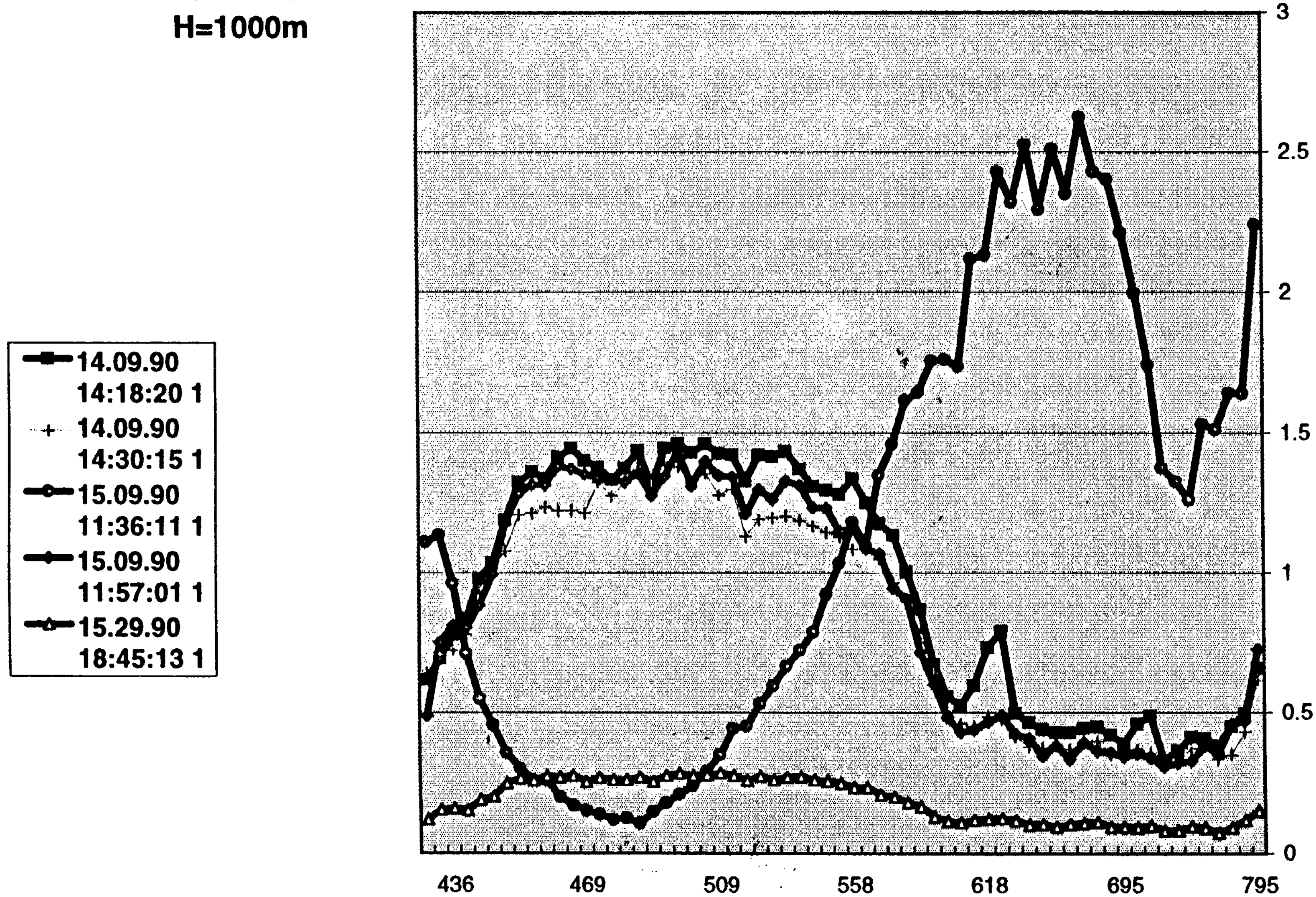


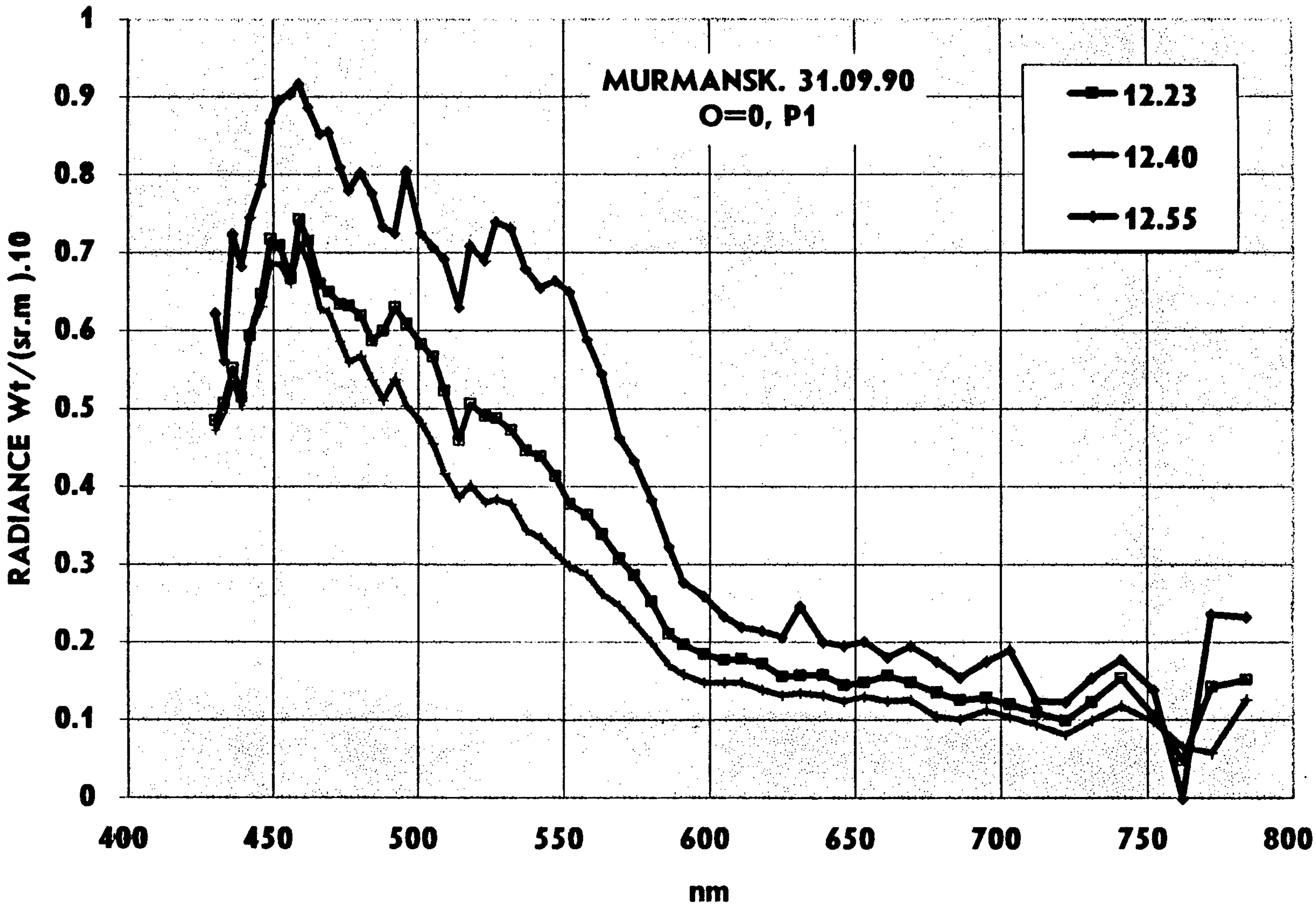

BLACK SEA. 28.05.88
A=0(1),180, H=3500m 9.25-10.29, P2
O=20
O=20
O=40
COEFFICIENT OF WATER RADIANCE
0
0.5
1
1.5
2
2.5
3
3.5
4
400
450
500
550
600
650
700
750
nm

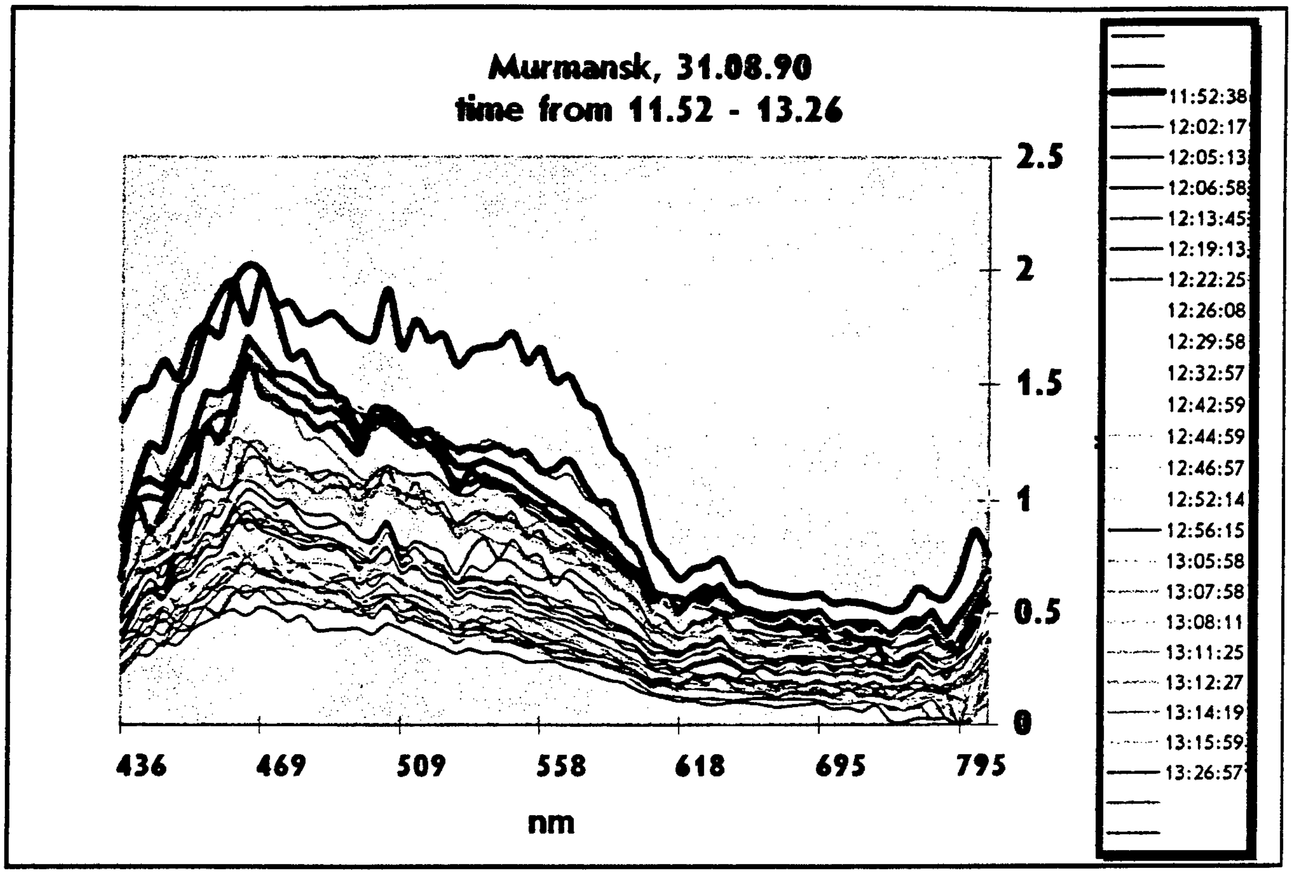

JAPAN SEA. 22.09.88
A=90(2),A=270,12.53-12.58,H=3600 m,P1
O=10
O=0
O=10
O=20
RADIANCE Wt/(sr.m).10
nm
0
0.5
1
1.5
2
2.5
3
3.5
4
400
450
500
550
600
650
700
750


MURMANSK. 31.09.90
O=0, P1
13.06
13.08
13.11
RADIANCE Wt/(sr.m).10
1.4
1.2
1
0.8
0.6
0.4
0.2
0
400
450
500
550
600
650
700
750
800
nm

# Black Sea and Land
H=1000m

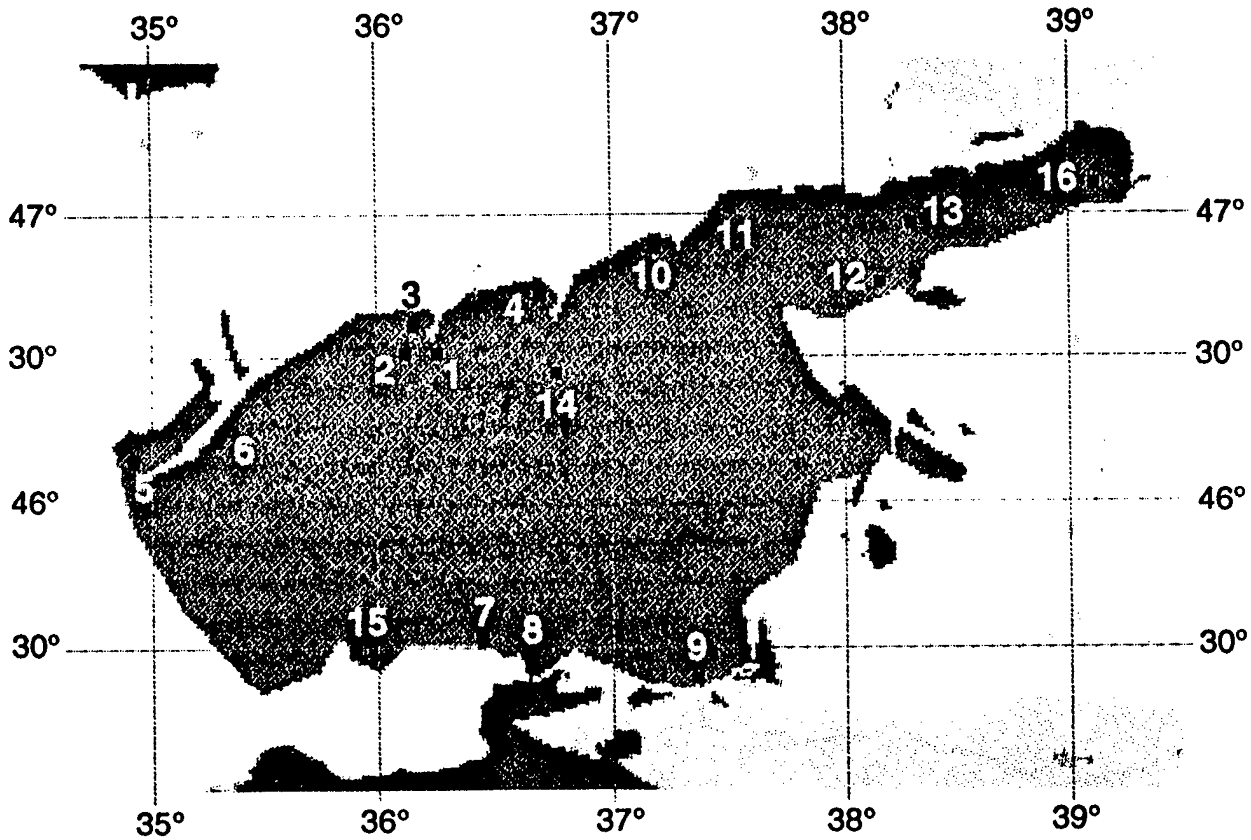



MURMANSK. 31.09.90
O=0, P1
12.23
12.40
12.55
RADIANCE Wt/(sr.m).10
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
400
450
500
550
600
650
700
750
800
nm

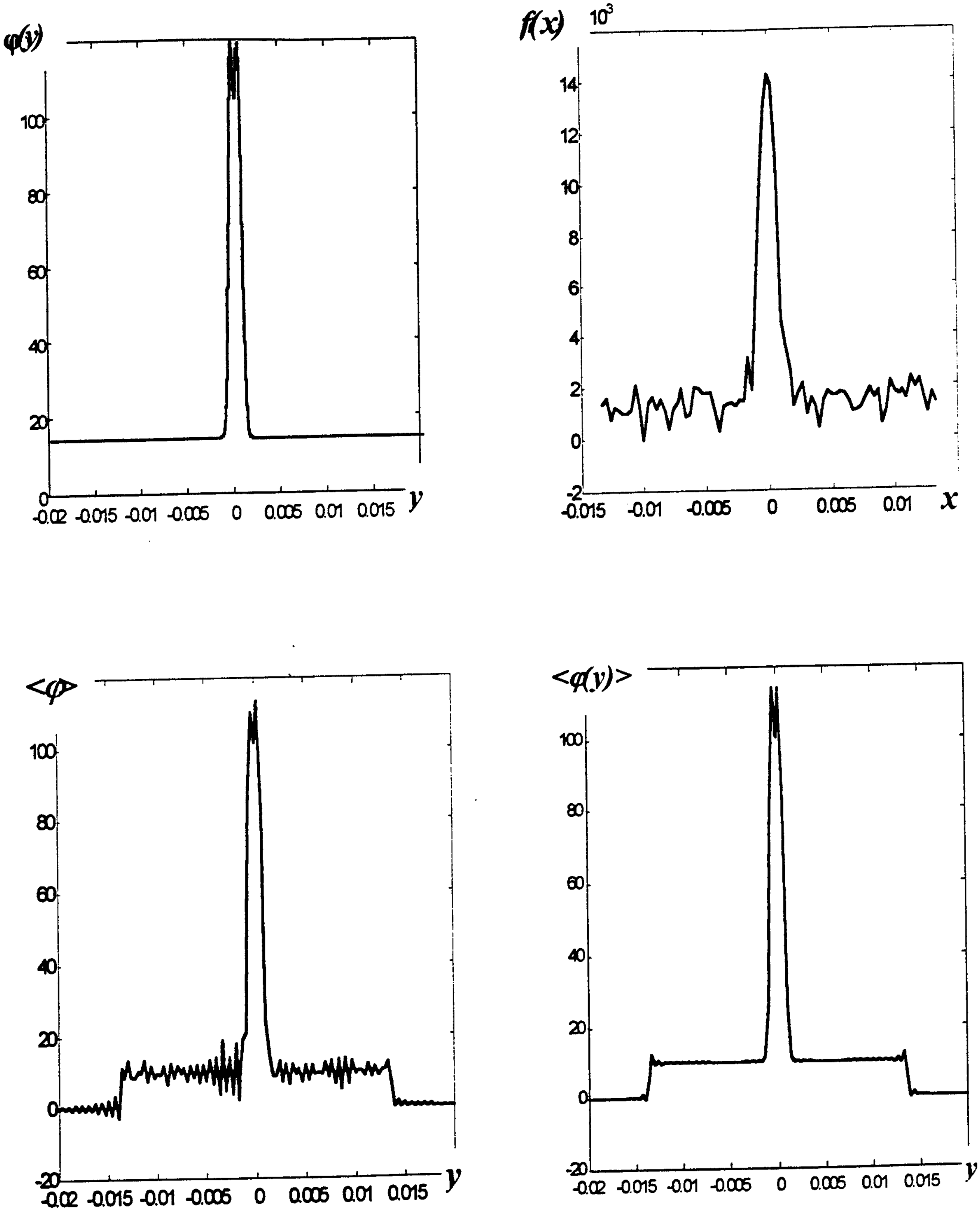


Murmansk, 31.08.90
time from 11.52 - 13.26
2.5
2
1.5
1
0.5
0
436
469
509
558
618
695
795
nm
11:52:38
12:02:17
12:05:13
12:06:58
12:13:45
12:19:13
12:22:25
12:26:08
12:29:58
12:32:57
12:42:59
12:44:59
12:46:57
12:52:14
12:56:15
13:05:58
13:07:58
13:08:11
13:11:25
13:12:27
13:14:19
13:15:59
13:26:57

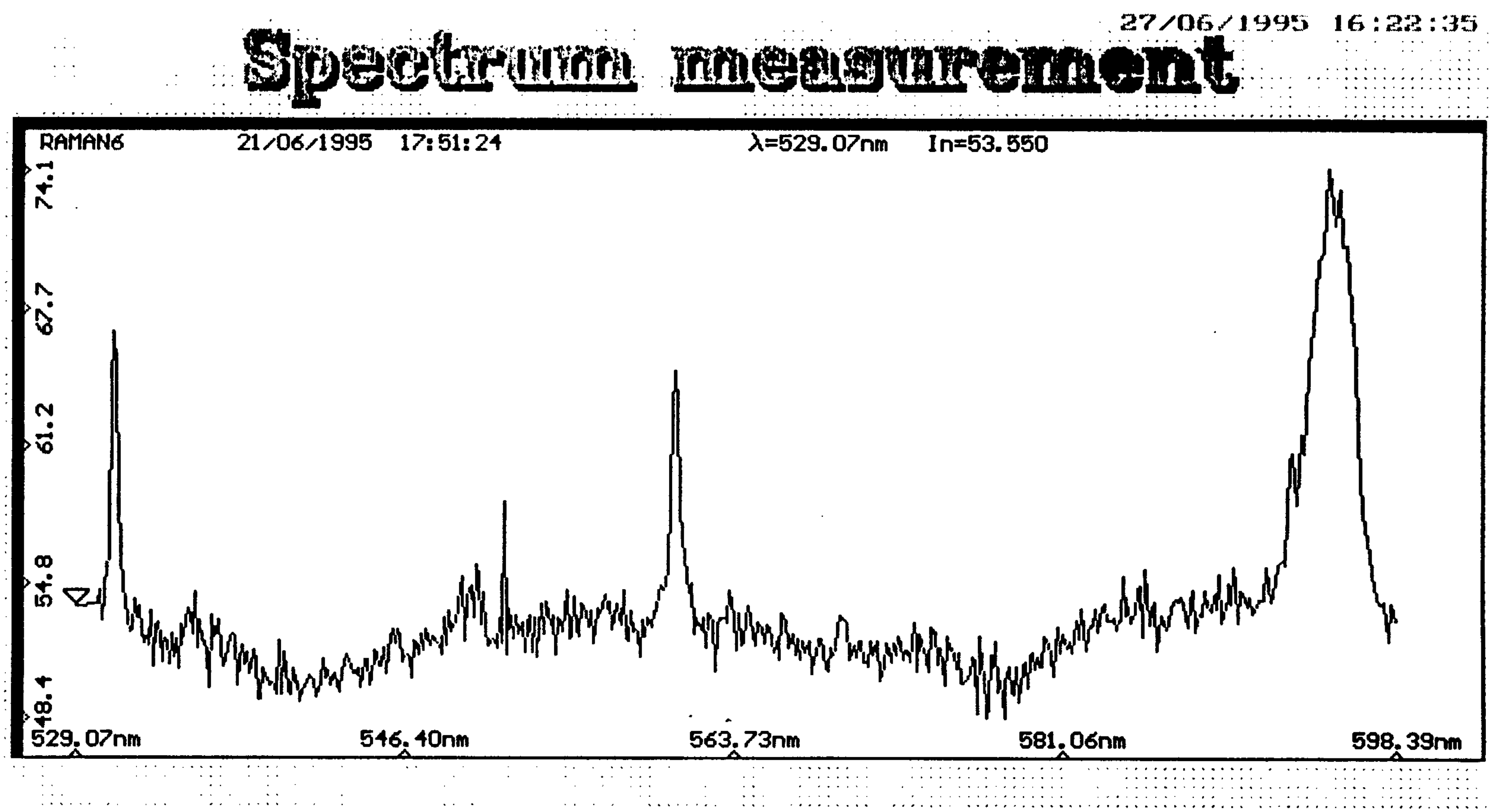
SEA OF AZOV DATA POINTS



EDP-503-01-pm

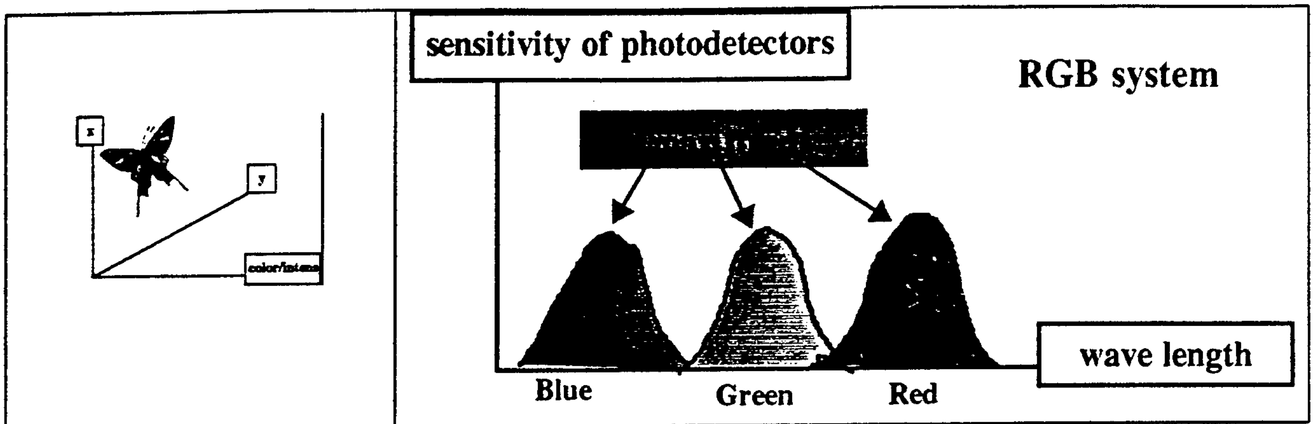


Enhanced spectral resolution derived from special analysis of spectrogram



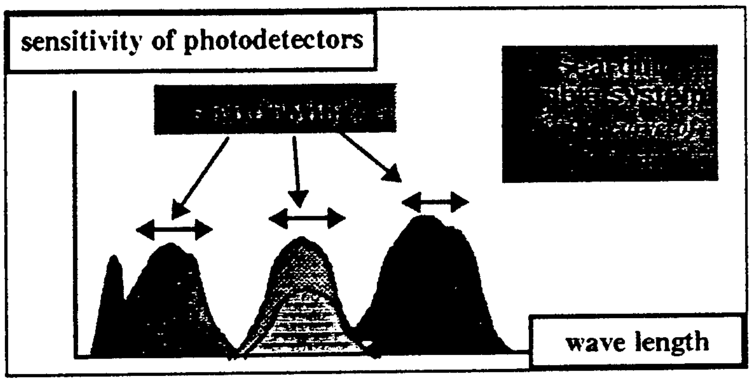
Raman Spectrum of TCE

Human and Sea-gull Vision System

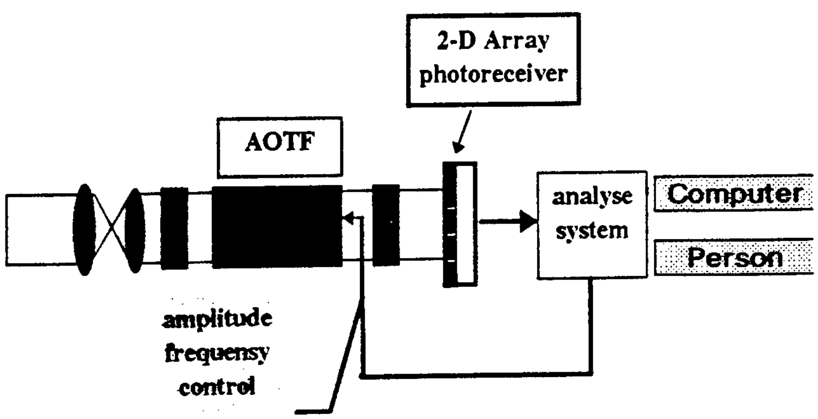


The curves of sensitivity of eyes (photodetectors) has three fixed maximums

The curves of sensitivity of eyes (photodetectors) of Sea-Gull vision system has three fixed maximums, which can move on spectral axis



Acousto-Optical System for the transmission, processing, and recognition of images

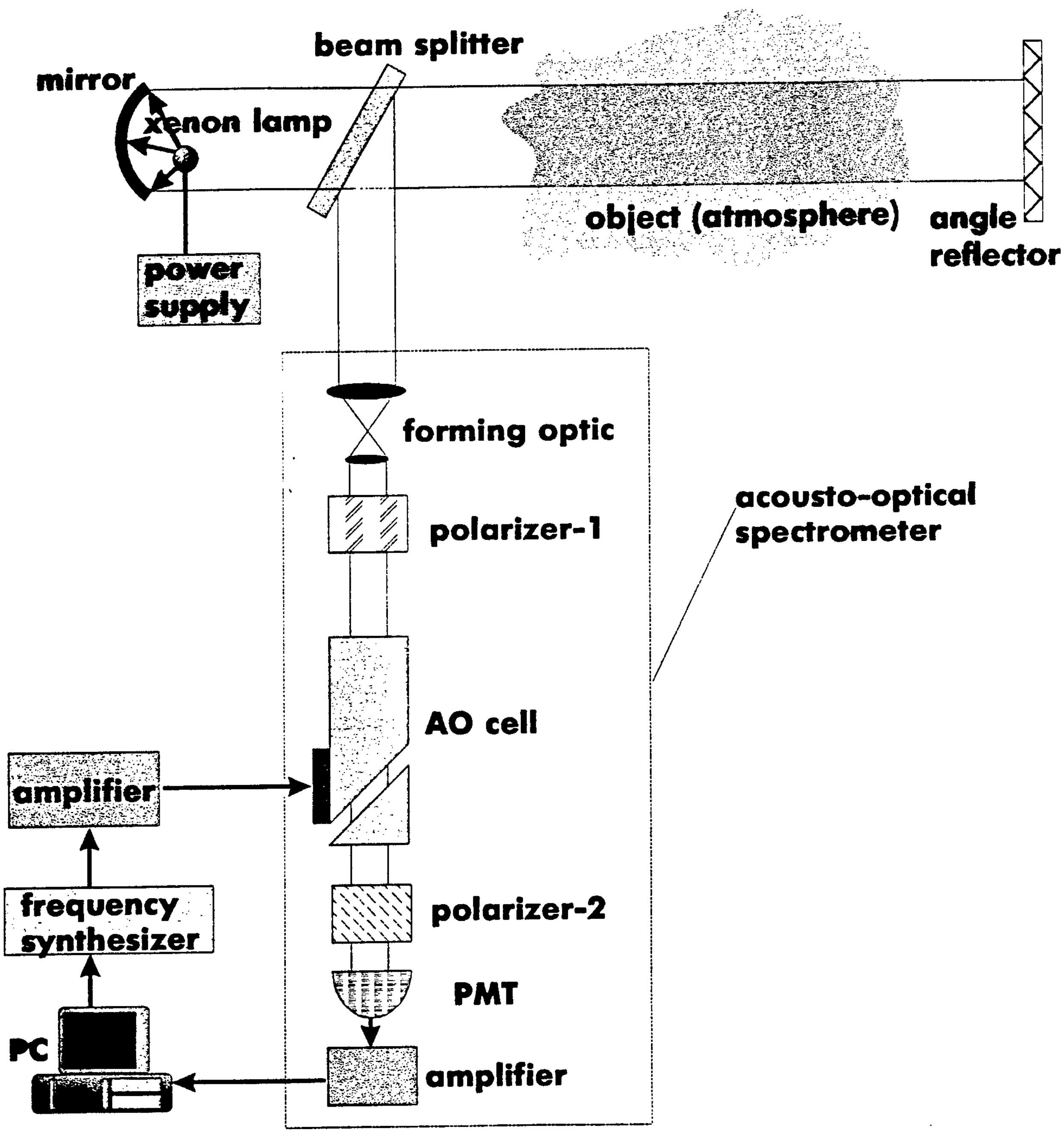


(V.E.Pozhar and V.I.Pustovoit.
Радиотехника и электроника, 1996,v.41, №10)

Pollution Detection Threshold

	SAGA-K		SAGA-T	
Measured pollutant	Detection Threshold, ppm, not greater, cell 75cm	Maximum measured concentration ppm, not greater, cell 20cm	Detection Threshold, ppm, not greater, path 200m	Maximum measured concentration ppm, not less, path 30m
Sulfur dioxide, SO_2	2	4500	0,02	50
Nitrogen dioxide, NO_2	5	3000	0,02	40
Carbon disulphide, CS_2	14	4000	0,02	100
Ozone, O_3	20	5000	0,02	100
Chlorine, Cl_2	20	6000	0,1	100
Formaldehide, H_2CO	20	6000	0,1	100
Benzene, C_6H_6	2	1000	0,03	10
Toluene, C_6H_5-CH_3	3	1500	0,04	15
Phenol, C_6H_5OH	0,6	100	0,003	1
Naphtalene, $C_{10}H_8$	0,7	120	0,003	0,5
Pyrene, $C_{16}H_{10}$	0,3	12	0,002	0,3
p-Xylene, C_8H_{10}	100	2000	0,5	250
m-Xylene, C_8H_{10}	2	1200	0,03	12
o-Xylene, C_8H_{10}	4	3000	0,06	30
Acetone, $(CH_3)_2CO$	10	5000	0,3	50

OPTICAL SCHEME OF ATMOSPHERIC POLLUTION MEASUREMENT



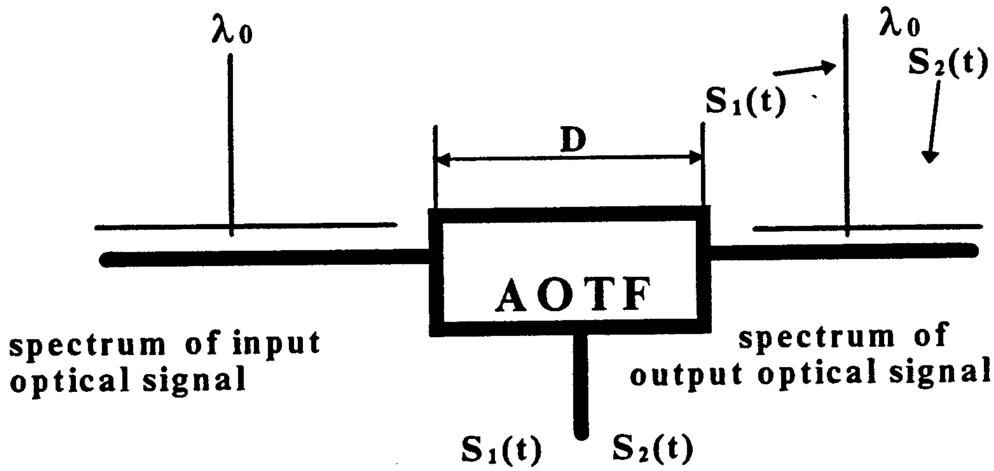
Recent Advances in AOTF Design and Fabrication at St.Petersburg State Academy of Aerospace Instrumentation

V.V.Kludzin, S.V.Kulakov, V.V.Molotok
St. Petersburg State Academy of Aerospace Instrumentation,
Laboratory of Acousto - Optic Systems,
67 B.Morskaia St., St.Petersburg, 190000, Russia,
Phone/FAX: +7 (812) 108-4204, E-mail:molotok@softjoys.ru

1. The main advantages of the acoustooptic tunable filters (AOTF)

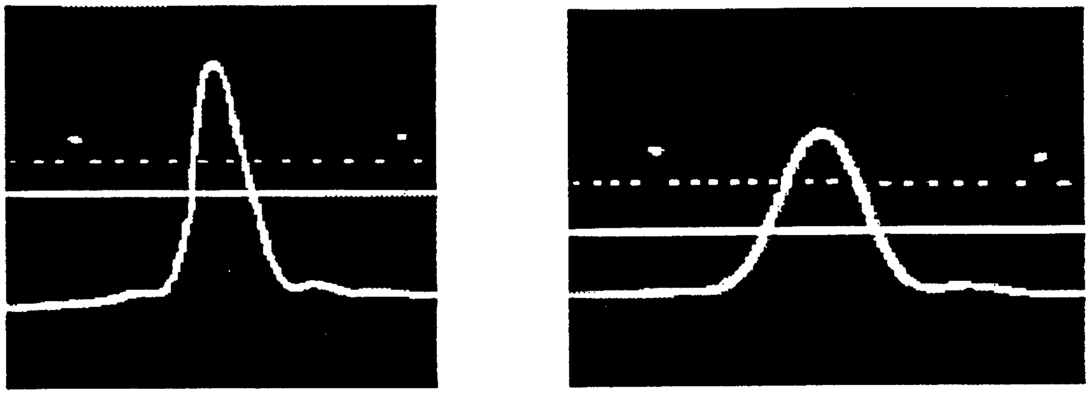
1. **Controllable tuning by an electronic signal**
2. **Fast switching speed**
3. **Extended angular aperture**
4. **Compatibility with electronic analog and digital modules**
5. **simple design and small sizes**

4. AOTF used for modulating spectrum width of a wideband optical signal.



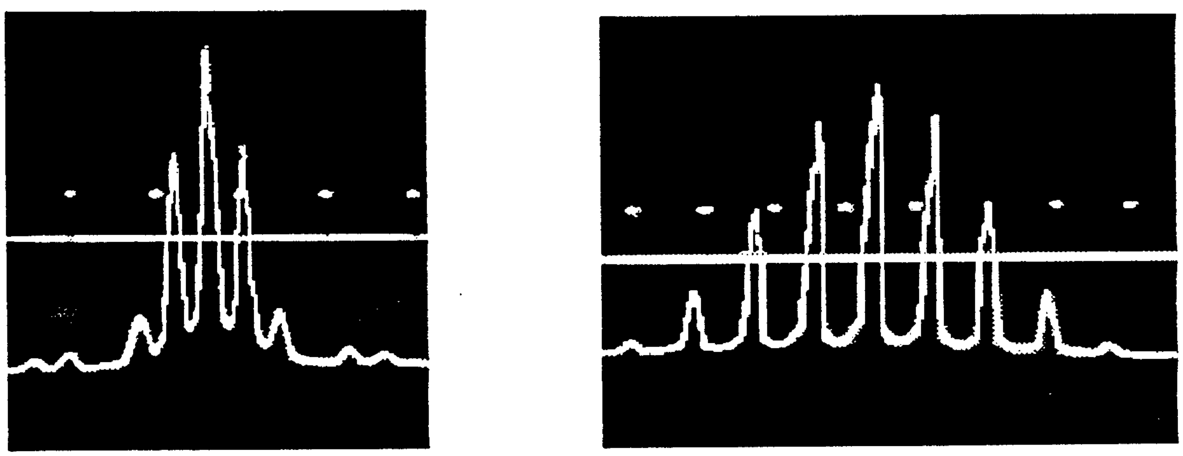
$T \leq D/v$ - clock rate

$0 < \tau < T; \quad \delta\lambda = k\tau$



a) (τ=T) b) (τ=0.5T)

Fig.4. Spectral responses of $CaWO_4$ collinear AOTF



a) (τ=0.5T;T=0.5D/v) b) (τ=0.5T; T=0.25D/v)

Fig.5

5. AOTF used in spectrometry

Table 4. Spectrometer parameters

AOTF materials	Analysis range, μm	Control frequency range, MHz	Resolution, nm (λ=0.63 μm)	Transmission coefficient	Analysis time, ms	Interaction regimes
Water	0.4-0.7	28-50	2.5	0.5 $P \approx 0.1$ W	≥2	Isotropic
$PbMoO_4$	0.6-1.1	90-160	1.5	0.5 $P \approx 0.5$ W	1	Isotropic
$LiNbO_3$	0.5-1.0	7-14	6	0.65 $P \approx 0.2$ W	1	Sub-collinear
TeO_2	0.65-1.5	25-55	1.2	0.8 $P \approx 0.05$ W	>3.5	Quasi-collinear
$CaWO_4$	0.56-1.04	35-65	1.1	0.5 $P \approx 0.5$ W	5	Collinear $\Delta\Psi \approx 4.5°$

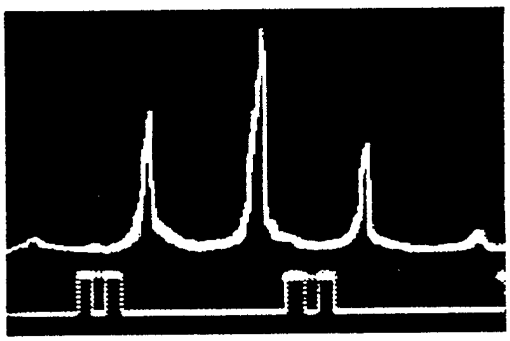


Fig. 6

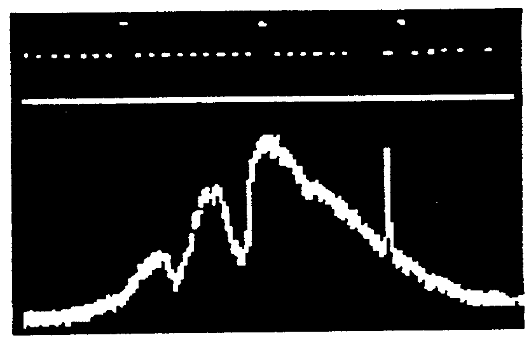
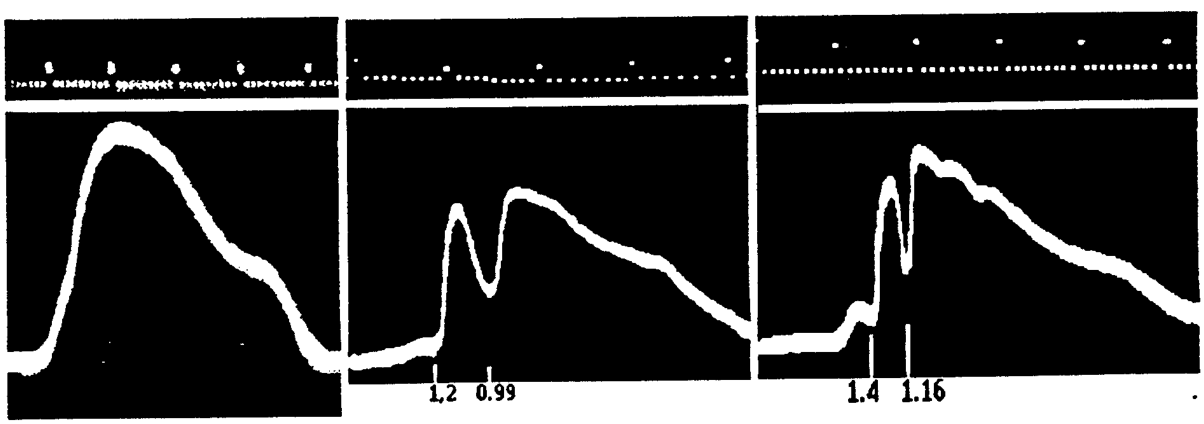


Fig.8



a) b) c)

Fig.7

Conclusion

1. Acousto-optic tunable filter have several advantages resulting from their electronic control and a large variety of available materials regimes.
2. The anisotropic regimes of acoustooptic interaction seems to be more perspective for the most applications.
3. In some cases, the advantages of isotropic media are worth remembering.

References

Design and Fabrication of Acoustoptic Devices. Ed.by A.Goutzoulis, D.Pape. Marcel Dekker Inc., New York, 1994

Dixon R.W. Acoustic diffraction of light in anisotropic media. IEEE Journ., QE-3, #2, 1967, p.85-93

Nien S.T.K., Harris S.E. Aperture-bandwidth characteristics of the filter. JOSA, 1972, v.62, #5, p.62-676

Yano T., Watanabe A. New noncollinear acoustooptic tunable filter using birefringence in TeO_2. Appl. Phys. Letters, 1978, v.24,#6, p.256-258

Chang I.C. Noncollinear acoustooptic filter with large angular aperture. Appl. Phys. Letters, 1974, v.25, p.370-373

Sivanaygam A., Findlay D. High resolution noncollinear acoustooptic filters with variable passband characteristics: design. Appl.Optics, 1984, v.233, #24, p.4601-4608.

Table 2. Physical parameters of acousto-optic materials

Material	Transparency range, μm	Refraction index (λ=0.63 μm)	Acoustic velocity $v*10^5$ cm/sec	Figure of merit, M_2*10^{-18} c^3/g	Range of control frequencies, MH (λ=0,63 μm)	Possible interaction regimes
TeO_2	0.36 - 5	n_0=2.26 n_e=2.41	0.617	600 - 1000	50 - 100	w/o collinear
$LiNbO_3$	0.4 - 4.5	n_0=2.28 n_e=2.2	3.9 6.57	3 - 8	400 - 600	all regimes
$CaWO_4$ ($CaMoO_4$)	0.4 - 4.5	$\Delta n=\|n_0-n_e\|=0.016$	2.3	~10	60	collinear
SiO_2	0.15 - 4	n_0=1.542 n_e=1.551	5.75	~2	80	all regimes
Tl_3AsSe_3	1.25 - 17	n_0=3.38 n_e=3.19 (λ=1.5μm)	1.0	~700	100 (λ=1.5μm)	all regimes

3. Normalization of the spectral response

For "slow" scanning regime

$\delta\lambda \sim \lambda^2$; $N=\Delta f D/v$ - number of resolvable points

Result of normalization

$$\delta\lambda(\lambda)=\delta\lambda(\lambda_{max})=Const$$

$$\text{if} \quad f(t)=f_0+bt^2$$

$$T=(N)^{0.5}D/v$$

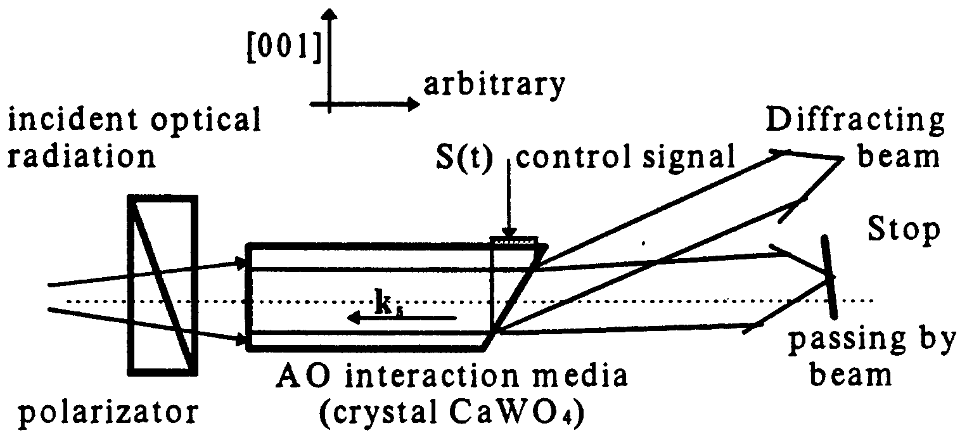


Fig.2. Collinear AOTF

2. The main parameters of AOTF

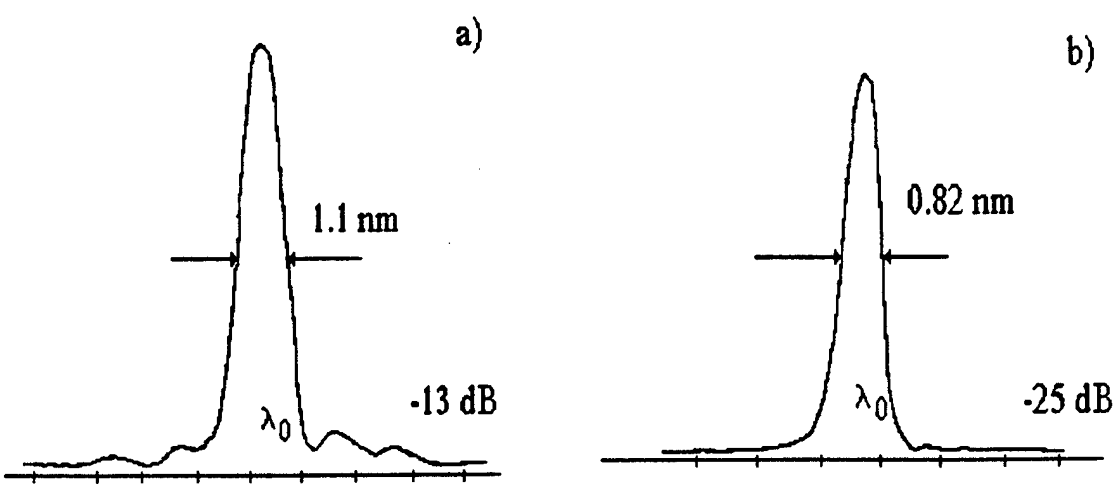
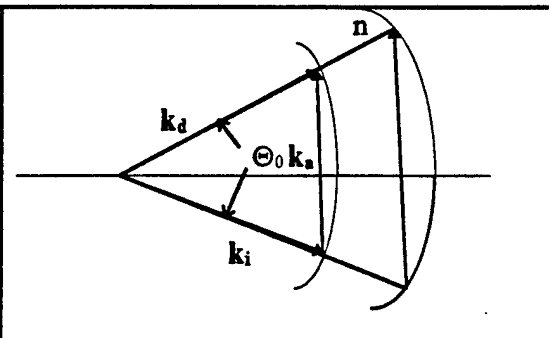
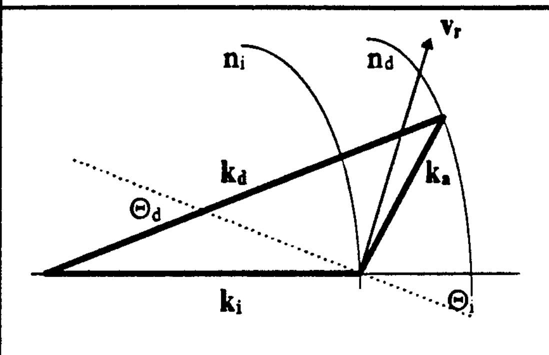
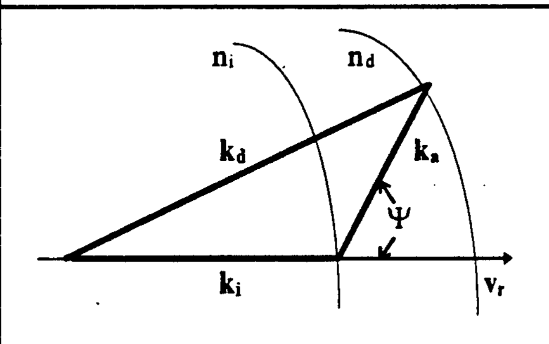
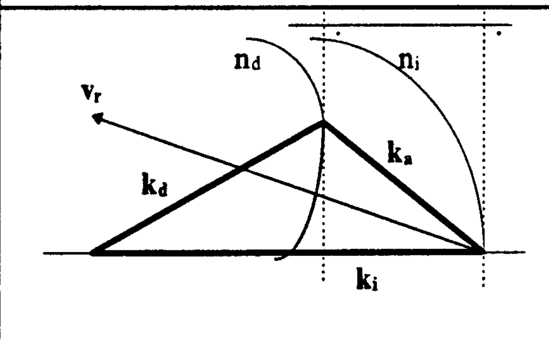
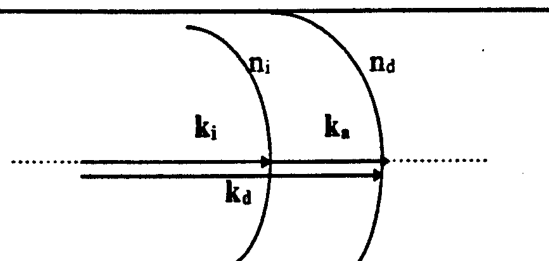


Fig.3. The spectral responses of AOTF (λ_0=0.63 μm)

Table 1. The geometry of different regimes of acousto-optic interaction

1		$\lambda f = n v \sin\Theta_0$ $k_a = \frac{2\pi f}{v}$, $k_i = k_d = \frac{2\pi n}{\lambda}$ $\delta\lambda \approx \frac{\lambda^2}{D\sin\Theta_0}$ ***isotropic***
2		$\lambda f = \Delta n_0 v \sin\Theta_i$ $k_i = \frac{2\pi n_i}{\lambda}$, $k_d = \frac{2\pi n_d}{\lambda}$ $\delta\lambda \approx \frac{\lambda^2 \cos\Theta_i}{\Delta n_0(\lambda) L \sin^2\Theta_i}$ ***quasicollinear***
3		$\lambda f \cong v \frac{\Delta n(\lambda, \Theta_i)}{\cos\Psi}$ ***subcollinear***
4		$\lambda f = \Delta n v \sqrt{(\sin^4\Theta_i + \sin^2 2\Theta_i)}$ $\delta\lambda \approx \frac{\lambda^2 \cos(\Theta_a - \Theta_i)}{\Delta n_0(\lambda) L \sin^2\Theta_i}$ $tg\Theta_i tg(\Theta_a - \Theta_i) = 2$ ***Tangential***
5		$\lambda f = \Delta n(\lambda) v$ $\delta\lambda = \frac{\lambda^2}{\Delta n(\lambda) L}$ ***collinear***

$$\Delta\Psi R = \text{const}$$

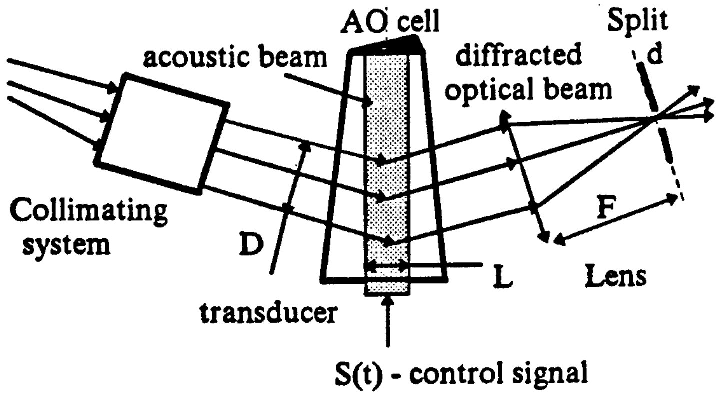


Fig.1. The isotropic acoustooptic tunable filter

$$d \leq \frac{k\lambda F}{D} \qquad R_s = \frac{fD}{v}, \qquad R_o = \frac{fL}{v}\tan\Theta_o,$$

$$R_s = R_0 \quad \rightarrow \quad \frac{\delta\lambda}{\lambda} = \frac{0.66}{R}, \quad g(\lambda) \sim \left\{\operatorname{sinc}[\pi R(\frac{\lambda}{\lambda_0} - 1)]\right\}^4$$

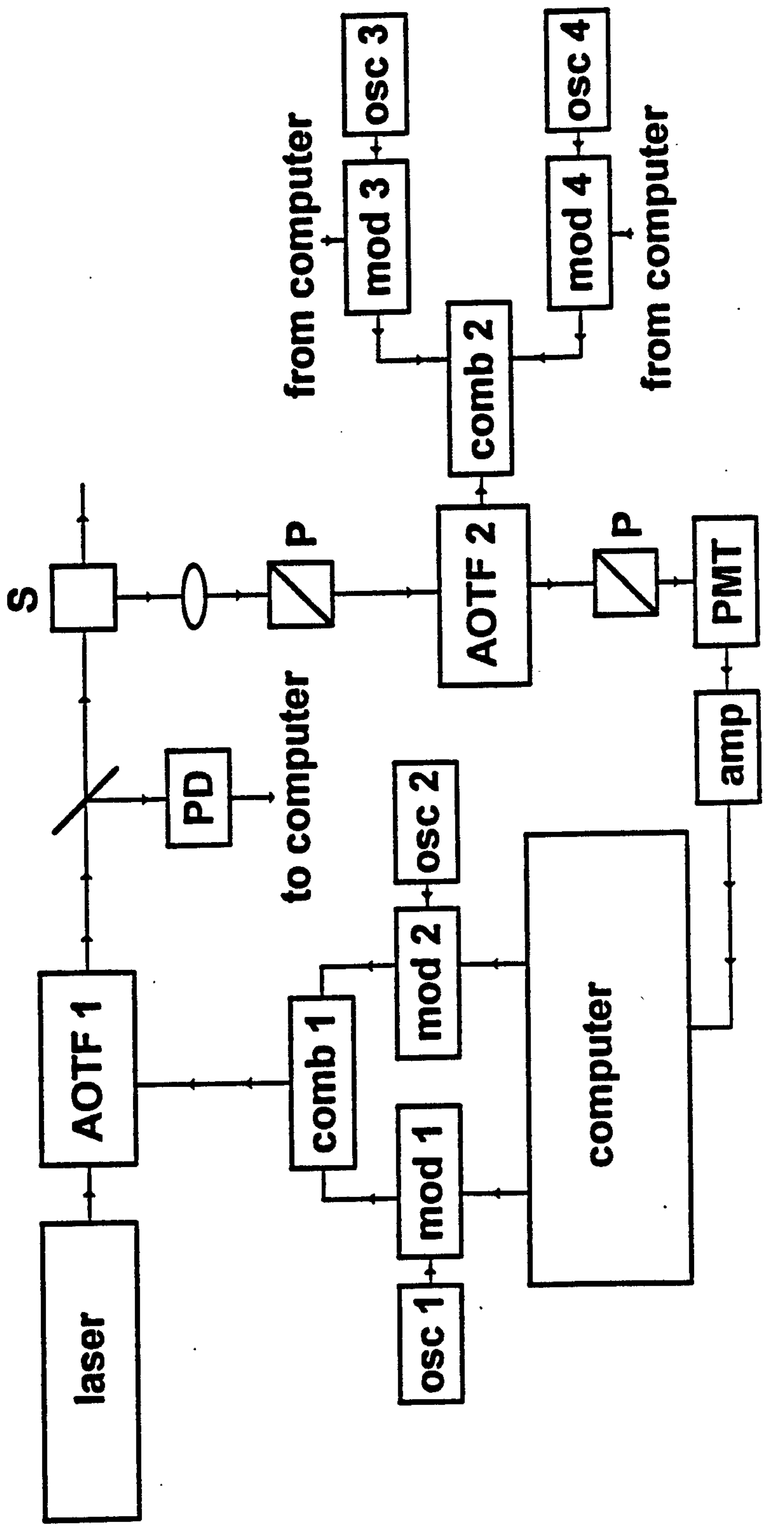
The advantages of isotropic interaction

1. The independence to the polarization of the input optical signal
2. More materials can be used in manufacturing of devices under different technical requirements
3. Large angular aperture in the plane orthogonal to the acousto-optic interaction plane
4. The isotropic materials are comparatively less expensive and their workpieces can be larger

Integrated Acousto-Optic Tunable Filters for Blue-Green Spectral Region

by

C. S. Tsai and A. M. Matteo, University of California, Irvine,


laser
AOTF 1
comb 1
mod 1
mod 2
osc 1
osc 2
computer
PD
to computer
S
P
AOTF 2
comb 2
mod 3
osc 3
mod 4
osc 4
from computer
from computer
P
PMT
amp

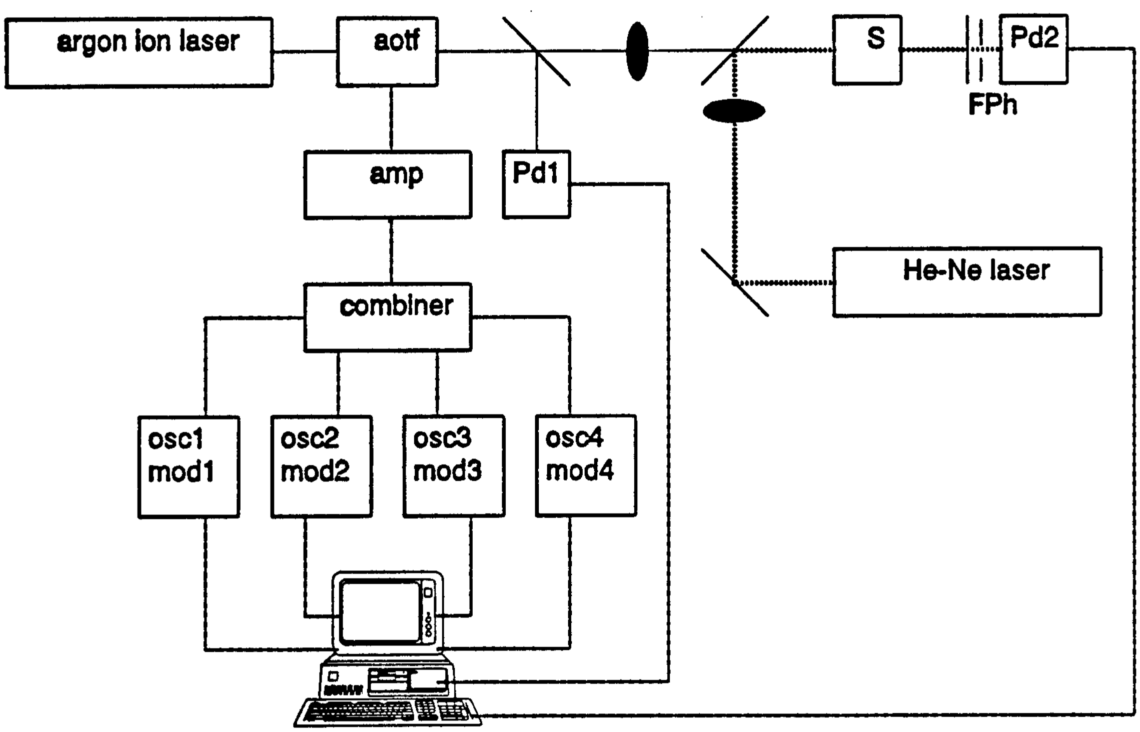

argon ion laser
aotf
S
Pd2
FPh
amp
Pd1
He-Ne laser
combiner
osc1
mod1
osc2
mod2
osc3
mod3
osc4
mod4

Fig. 2

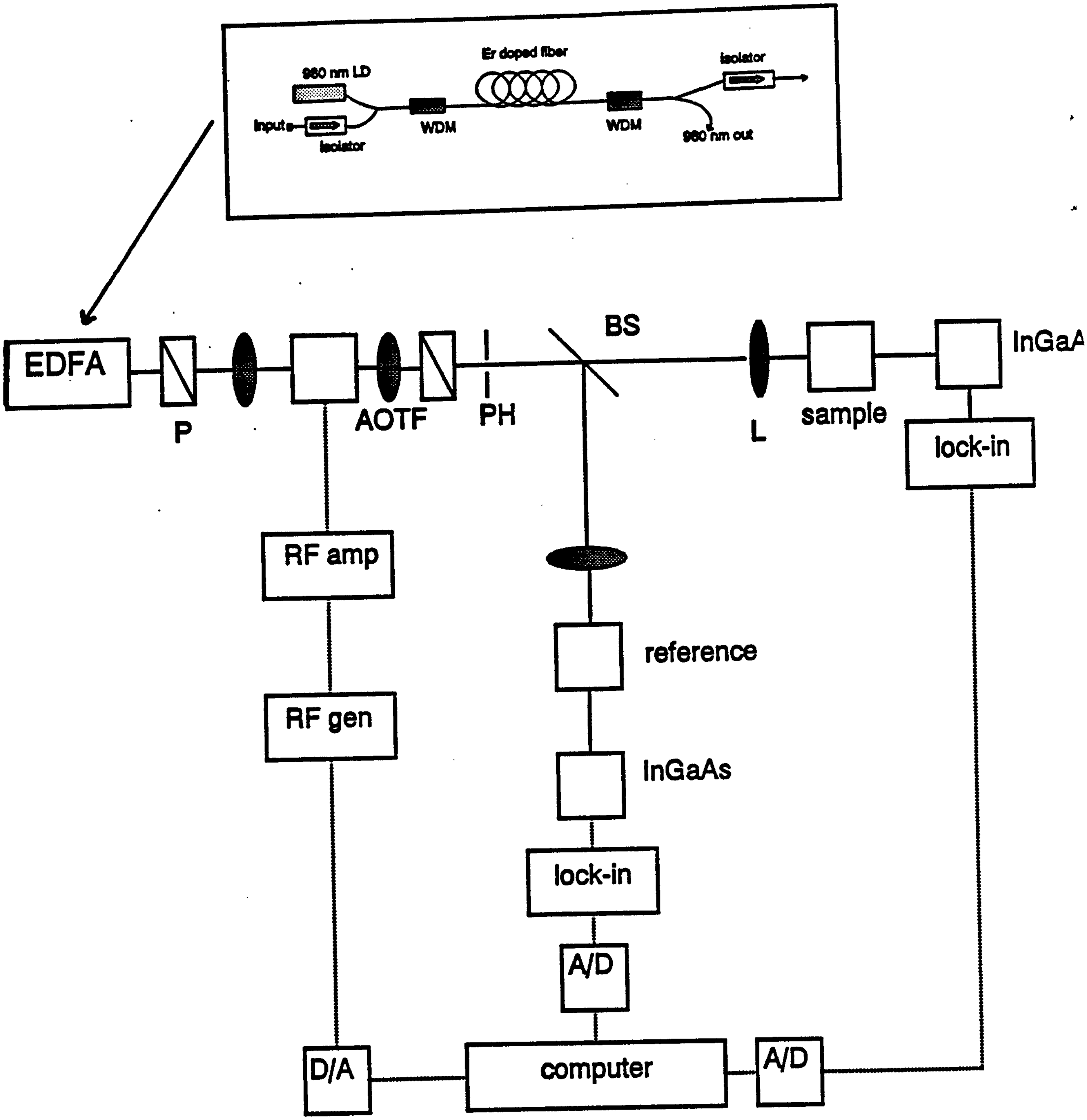
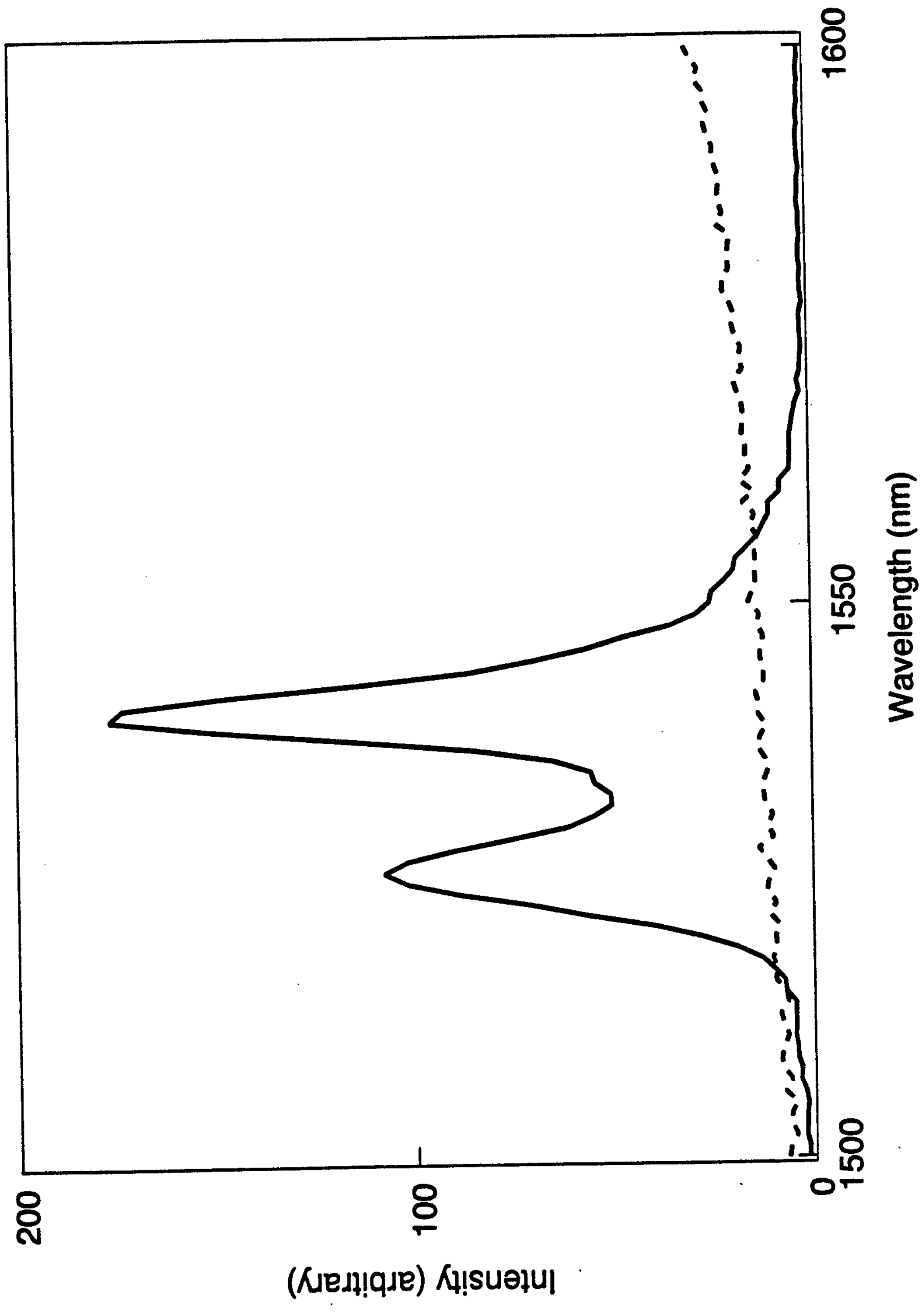
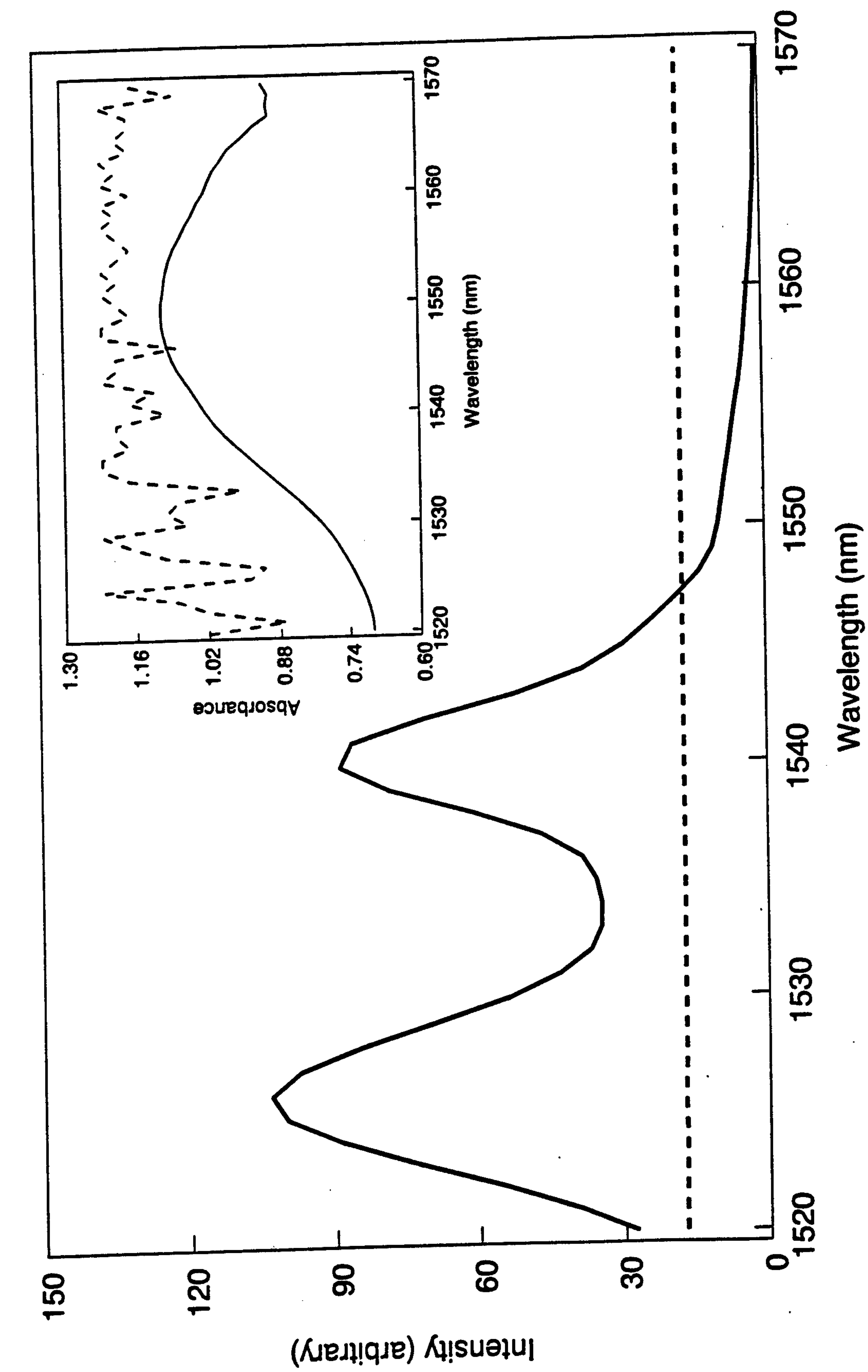

Er doped fiber
980 nm LD
isolator
input
isolator
WDM
WDM
980 nm out
EDFA
P
AOTF
PH
BS
L
sample
InGaA
lock-in
RF amp
RF gen
reference
InGaAs
lock-in
A/D
D/A
computer
A/D

Fig. 3


Intensity (arbitrary)
200
100
0
1500
1550
1600
Wavelength (nm)


Intensity (arbitrary)
150
120
90
60
30
0
1520
1530
1540
1550
1560
1570
Wavelength (nm)
Absorbance
1.30
1.16
1.02
0.88
0.74
0.60
Wavelength (nm)

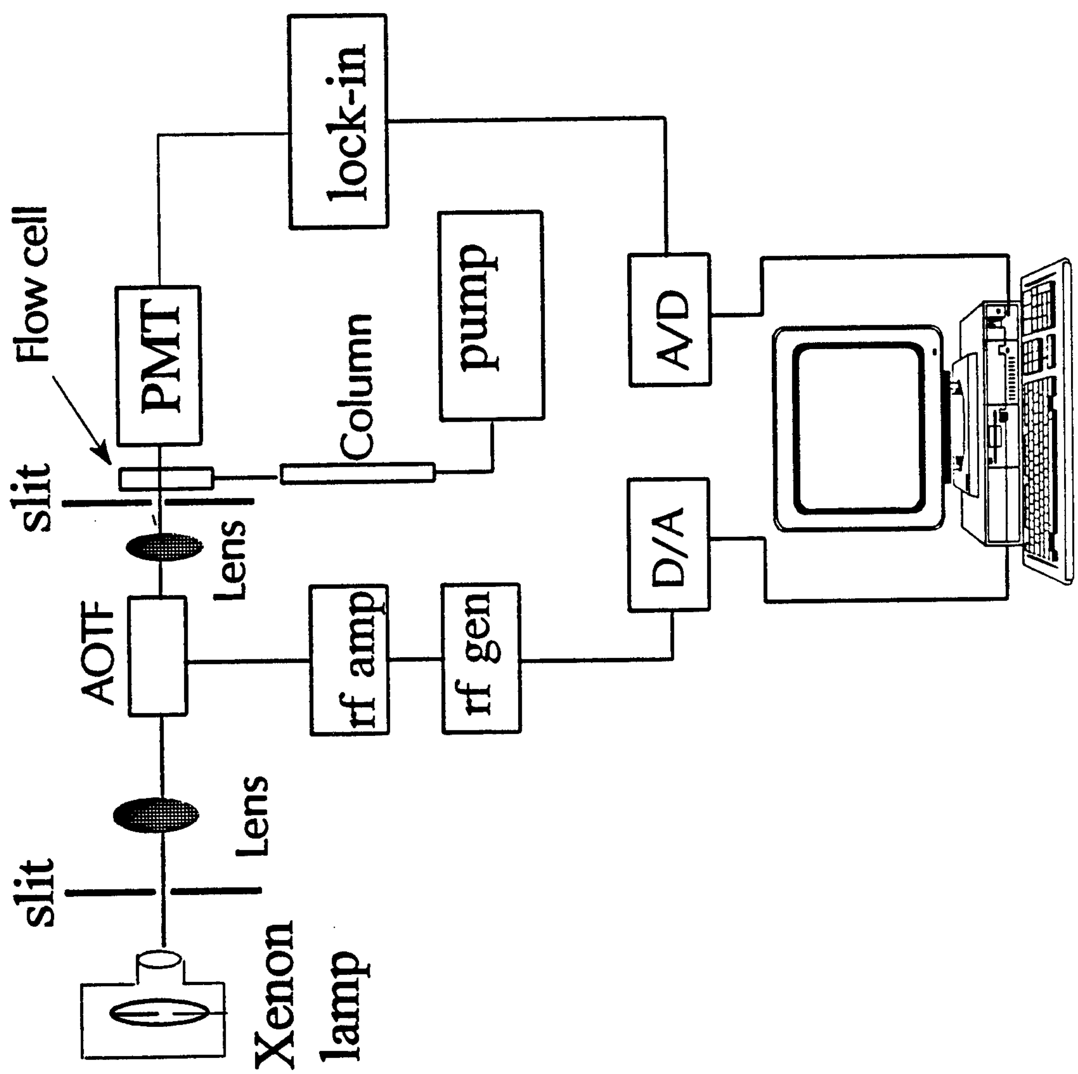

Xenon lamp
slit
Lens
AOTF
Lens
slit
Flow cell
PMT
Column
pump
rf amp
rf gen
lock-in
A/D
D/A

Fig. 6

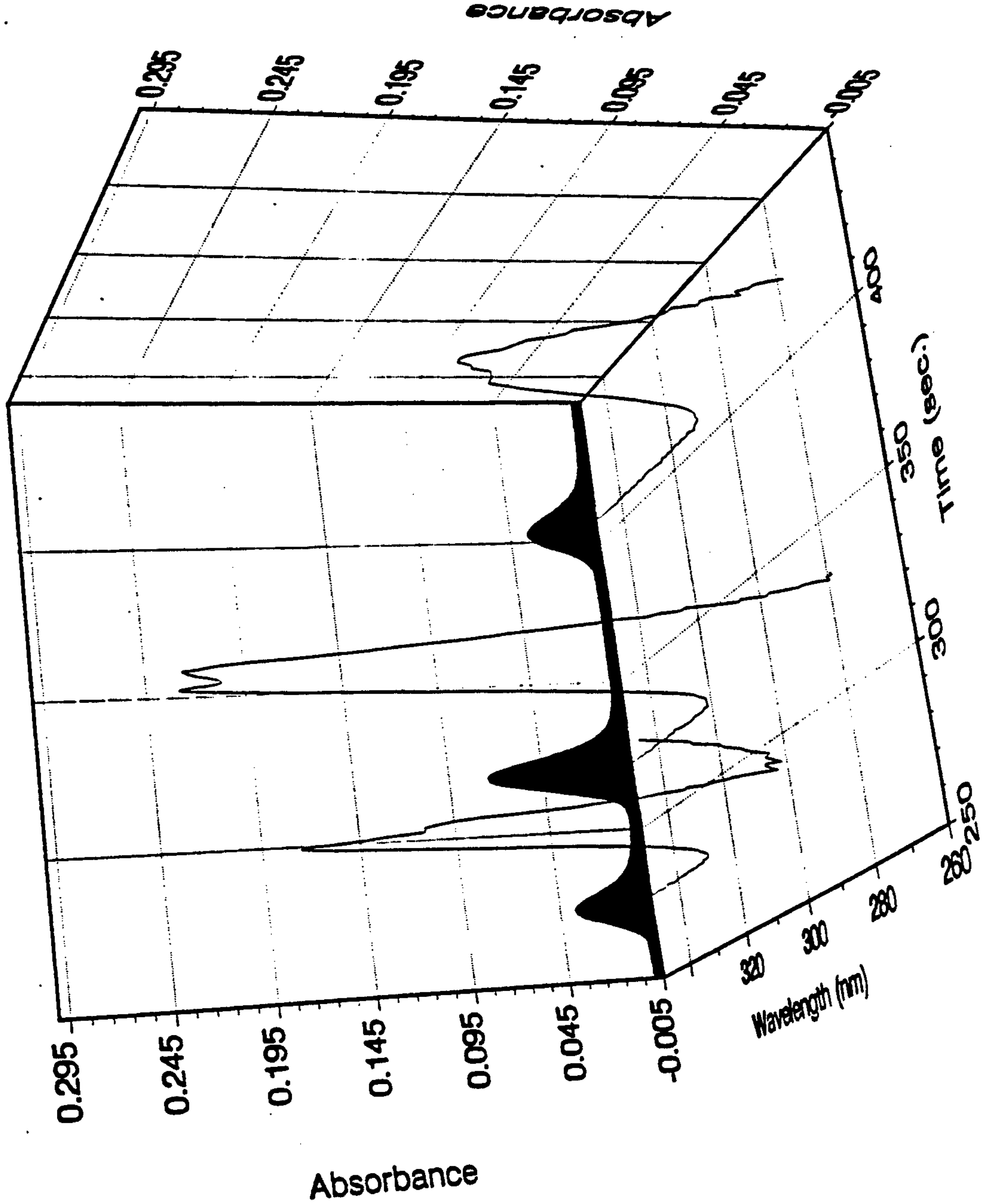
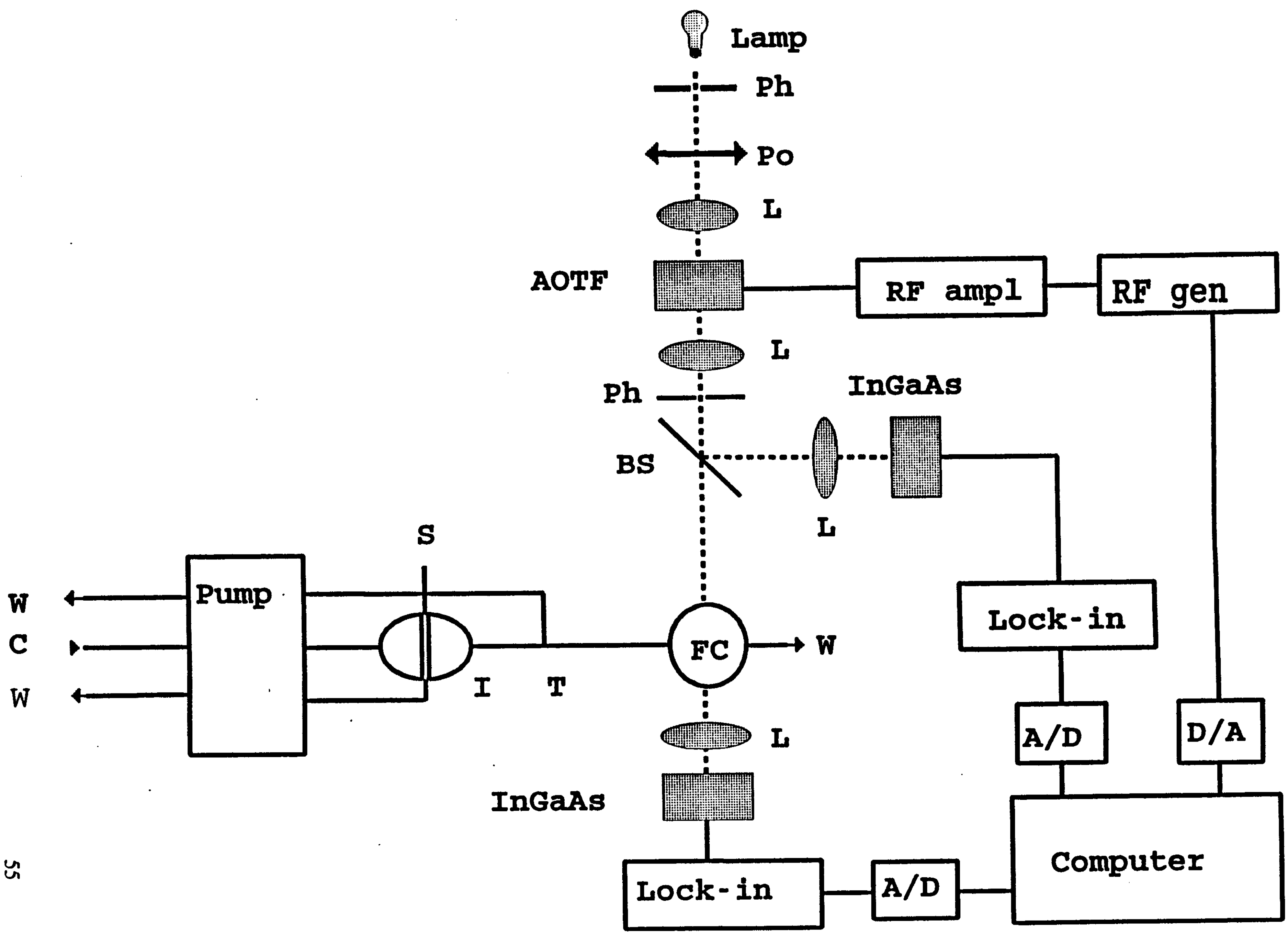
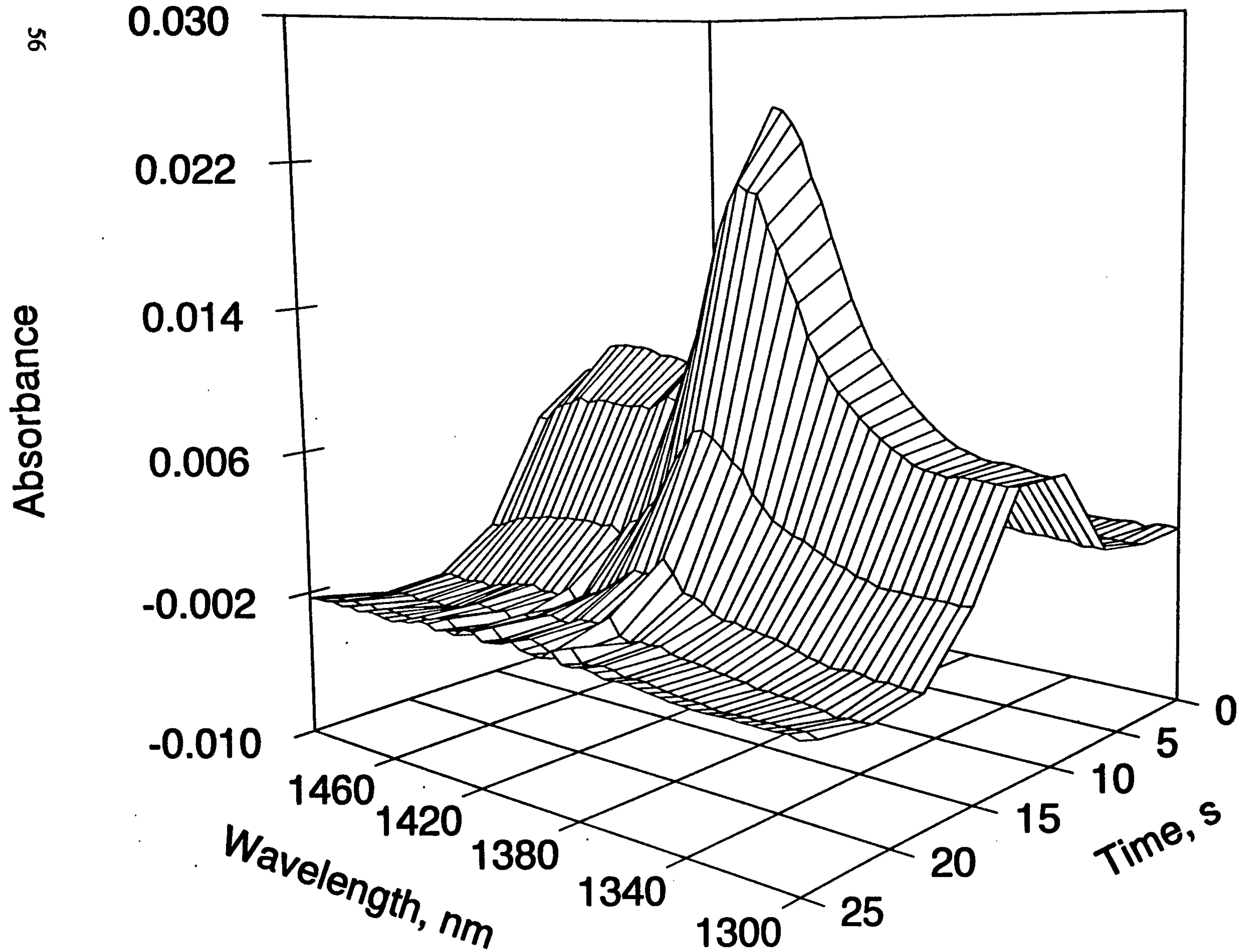
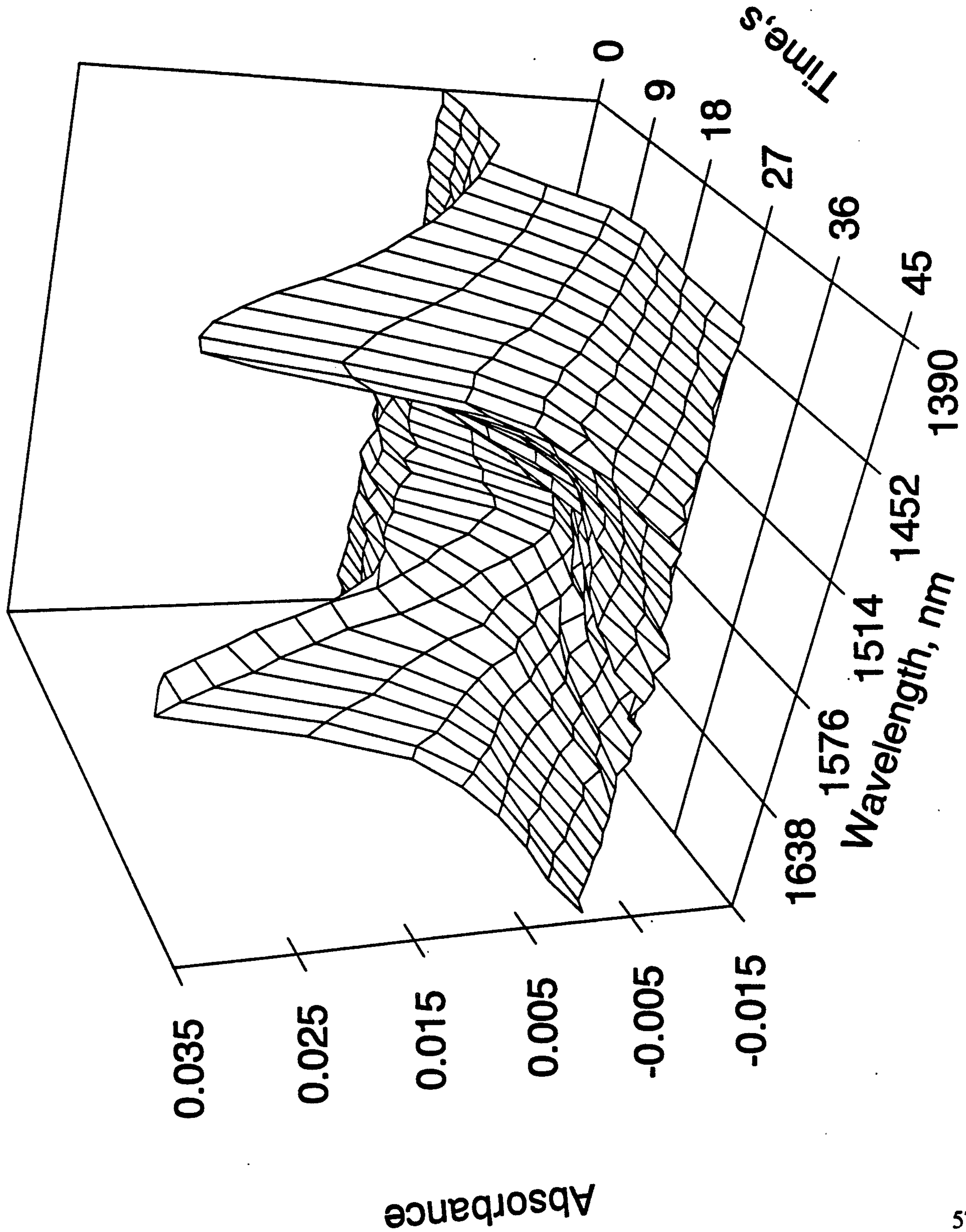

Absorbance
0.295
0.245
0.195
0.145
0.095
0.045
-0.005
Time (sec.)
400
350
300
250
Wavelength (nm)
320
300
280
260
Absorbance
0.295
0.245
0.195
0.145
0.095
0.045
-0.005

Fig. 7


Lamp
Ph
Po
L
AOTF
RF ampl
RF gen
L
Ph
InGaAs
BS
L
S
Pump
W
C
W
I
T
FC
W
Lock-in
L
A/D
D/A
InGaAs
Computer
Lock-in
A/D


Absorbance
0.030
0.022
0.014
0.006
-0.002
-0.010
1460
1420
1380
1340
1300
Wavelength, nm
0
5
10
15
20
25
Time, s


Absorbance
0.035
0.025
0.015
0.005
-0.005
-0.015
Time, s
0
9
18
27
36
45
Wavelength, nm
1390
1452
1514
1576
1638

APPLICATION OF AOTF TECHNOLOGY FOR CHEM/BIO DETECTION

Dr. Neelam Gupta* & *Dr. N. F. Fell, Jr.

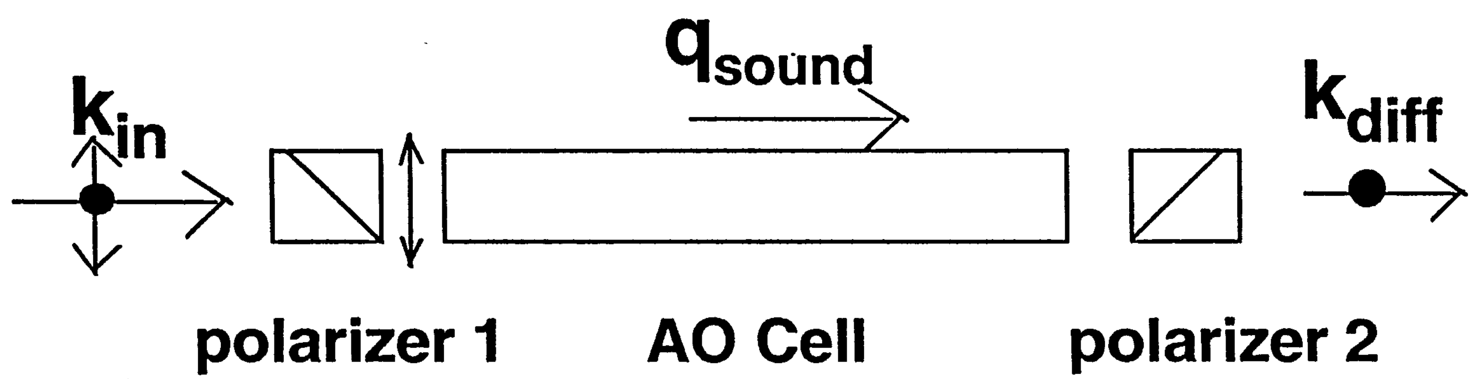
Sensors & Electron Devices Directorate
Army Research Lab
Adelphi, MD 20783

FIRST ARL WORKSHOP ON AOTF TECHNOLOGY

24-25 September 1996

Center for Adult Education, University of Maryland

COLLINEAR AOTF



$$f_{diff} = f_{in} + \Omega$$

$$k_{in} - k_{diff} - q = 0$$

$$\lambda = (n_o - n_e) v_s / \Omega$$

Spectral Resolution $\Delta\lambda/\lambda = \lambda / L\Delta n$

EXAMPLE: CRYSTAL QUARTZ AOTF

$n_o = 1.548, n_e = 1.539$

$v_s = 6.0 \times 10^5$ cm/sec

for visible band 400 nm < λ < 800 nm

135 MHz < Ω_{sound} < 68 MHz

COLLINEAR AOTF ADVANTAGES

- Lightweight, Compact, Portable
- No Moving Parts, Rugged
- Reliable
- Reproducible Operation
- Rapid Tuning and Scanning
- All Solid State Operation
- High Spectral Resolution
- Polarization Separation
- High Exticition Ratio

- Broad Tuning Range
- High Throughput
- Sequential or Random λ Access
- Capability for Multi λ Operation
- High Signal-to-Noise Ratio
- Uncooled Operation
- Programmable, Computer Control
- Arbitrary Spectral Signal Generation
- Flexible

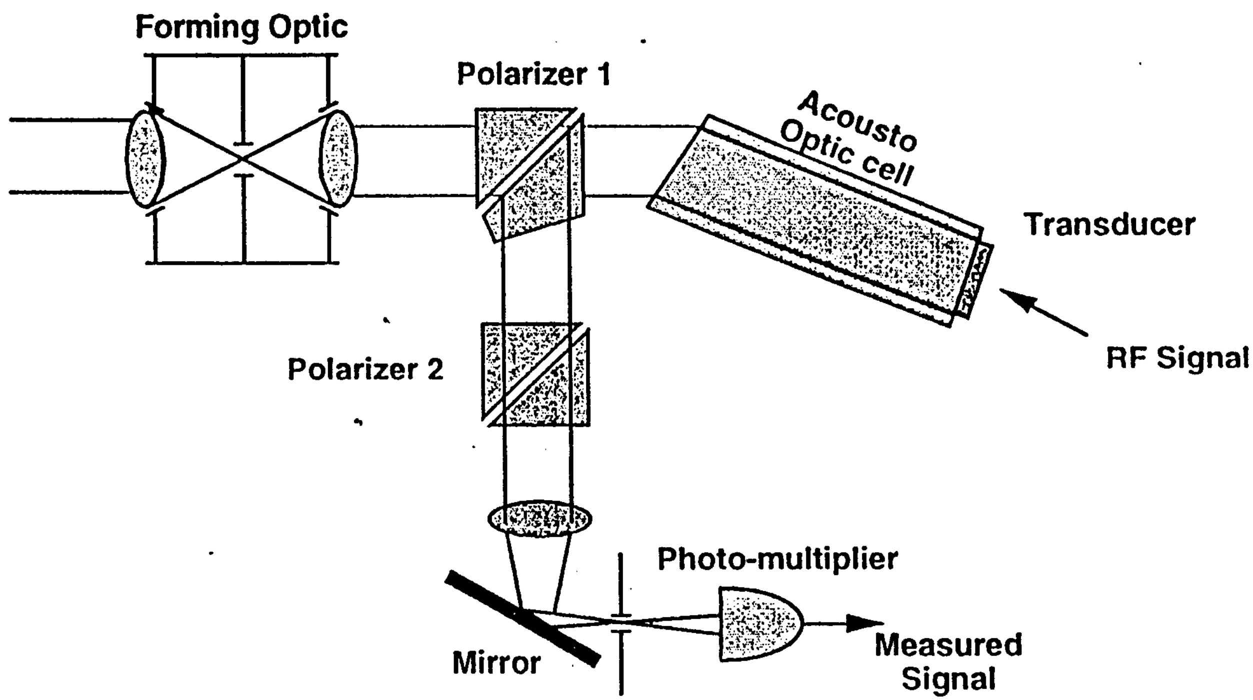
AOTF Specifications

	Quartz 4	Visible	UV
Spectral Range (nm)	420-785	400-800	255-430
Resolution (nm)	0.12-0.5	0.1-0.54	0.05-0.2
Position error (nm)	$\pm$ 0.5	$\pm$ 0.2	$\pm$ 0.2
Max Number of Points	4096	4790	7892
ADC Range	10 bits	12 bits	12 bits
Amplification	31	15	15
PMT Voltage Sensitivity	-	1:3:9:30	1:3:9:30
Effective Dynamic Range	31,744	1,843,200	1,843,200
Aperture	6 x 6 mm	6 x 6 mm	6 x 6 mm
Field of View	2°	2°	2°

AOTF APPLICATIONS AT ARL

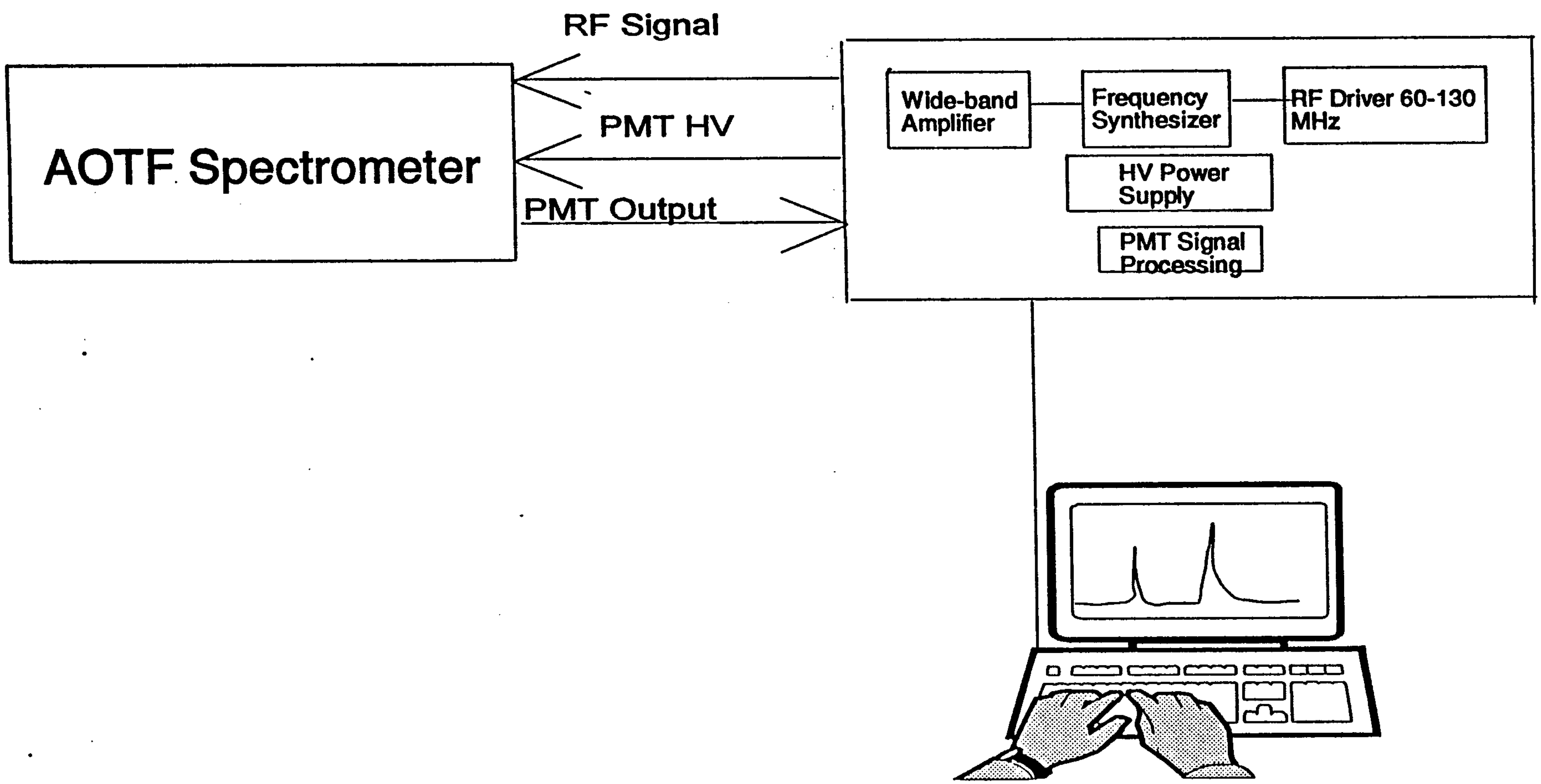
- Sensing of Chemical & Biological Agents: Fluorescence, Absorption, Emission, Raman, LIBS, etc.
- Remote Sensing/ Environmental Monitoring
- Multispectral and Hyperspectral Imaging
- Medical Applications; i.e. Blood Analysis
- Fire Sensing
- Polarization Spectroscopy

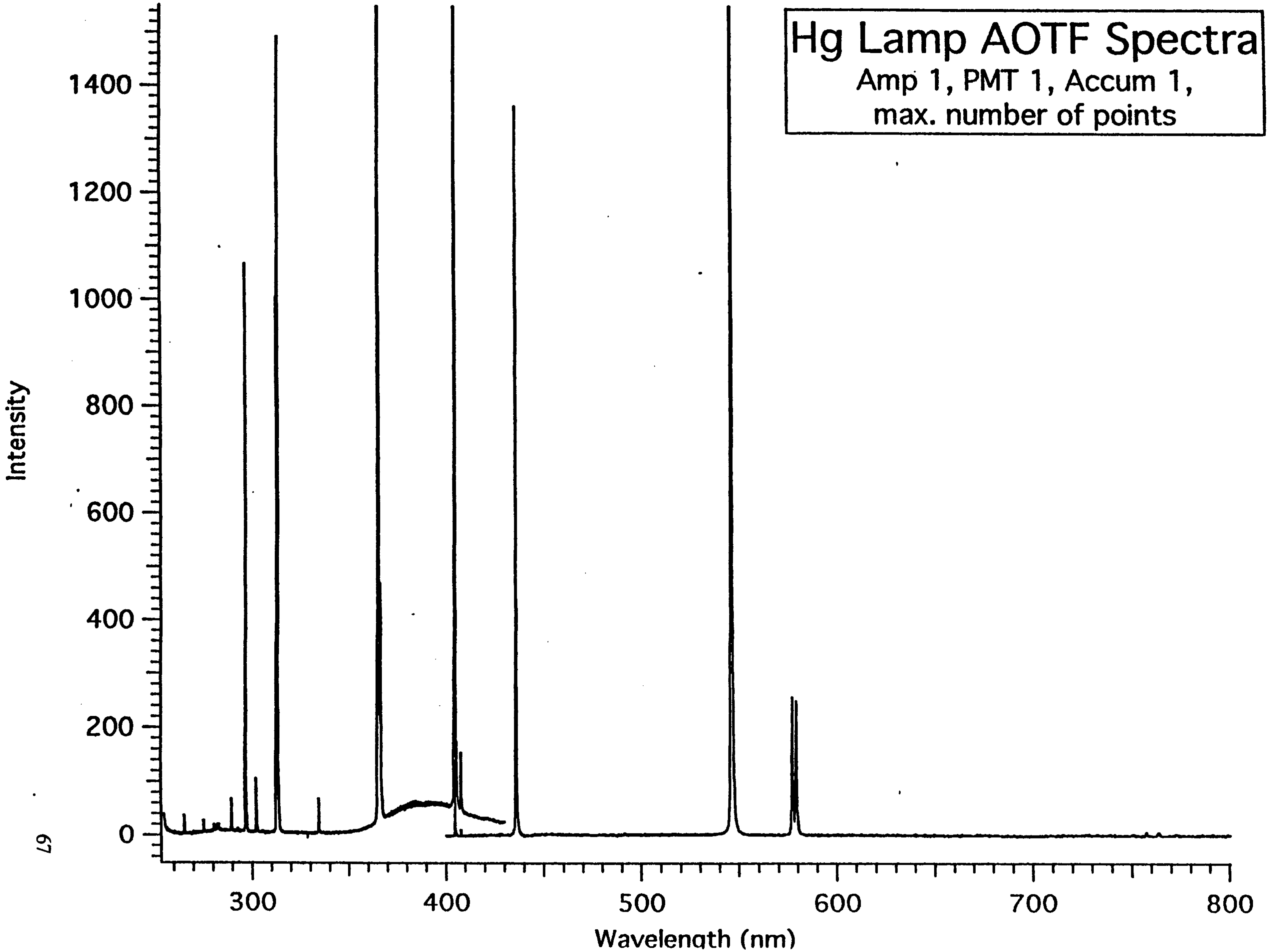
OPTICAL SCHEME OF ACOUSTIC SPECTROMETER "QUARTZ – 4"

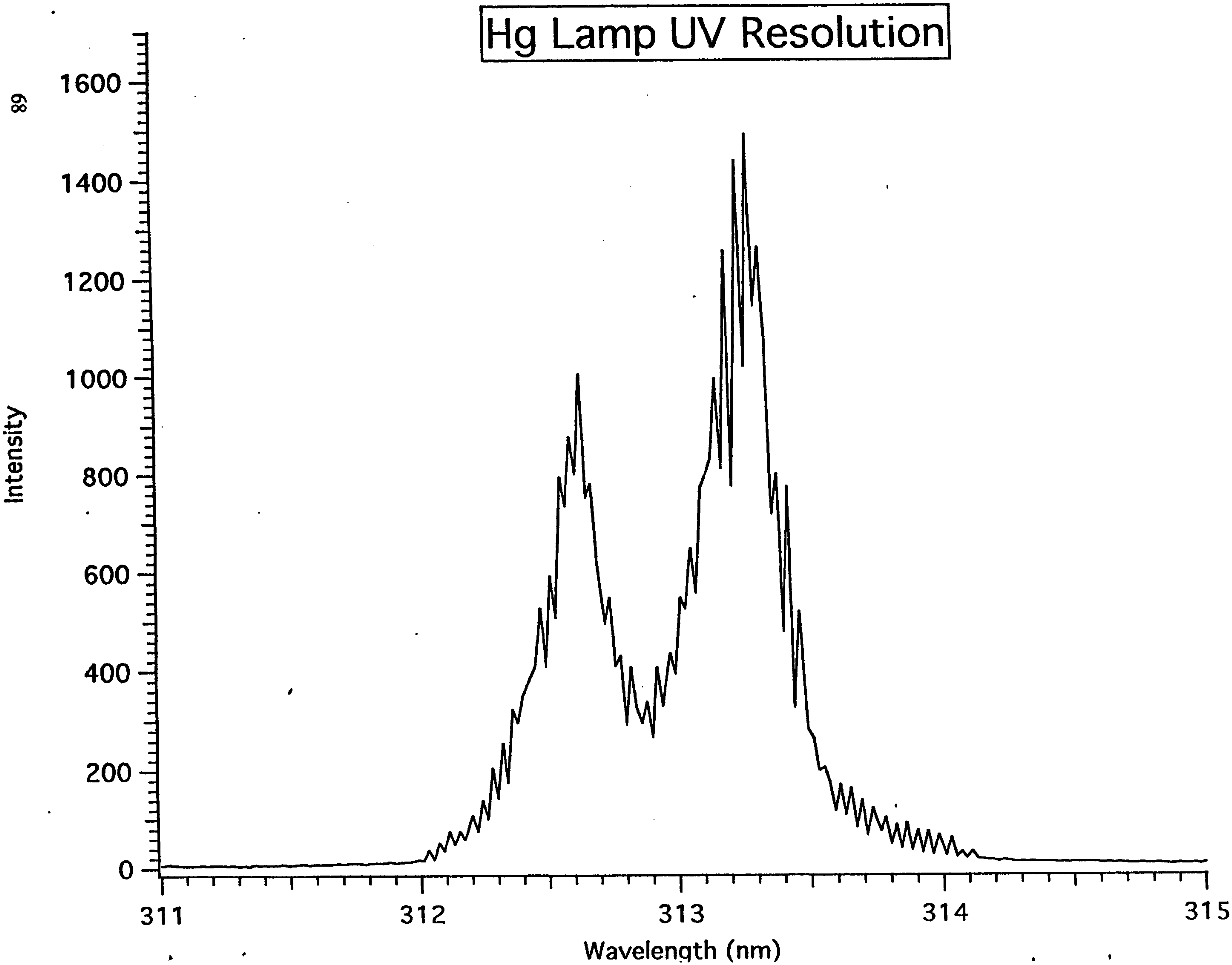


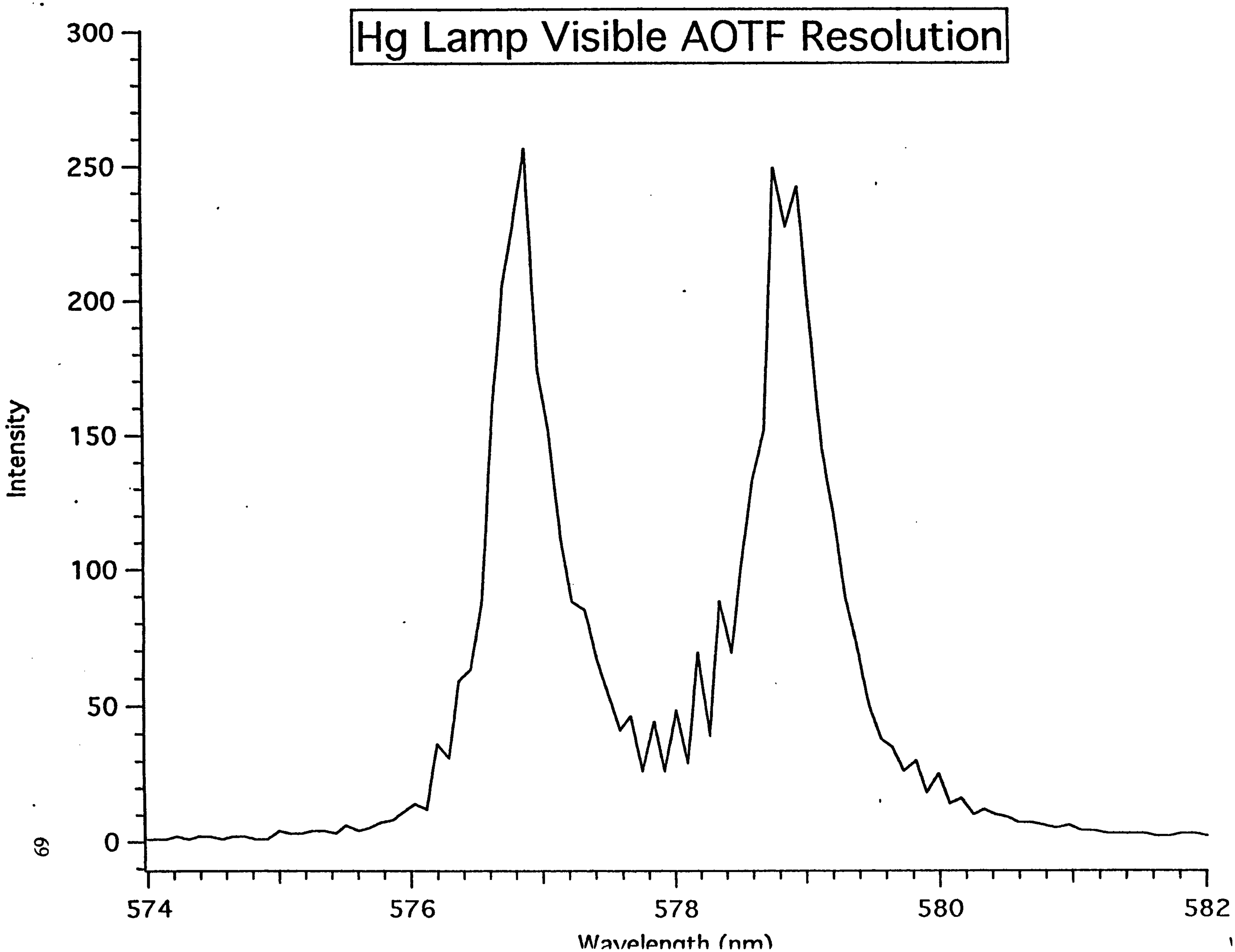
EOP-508-01-md

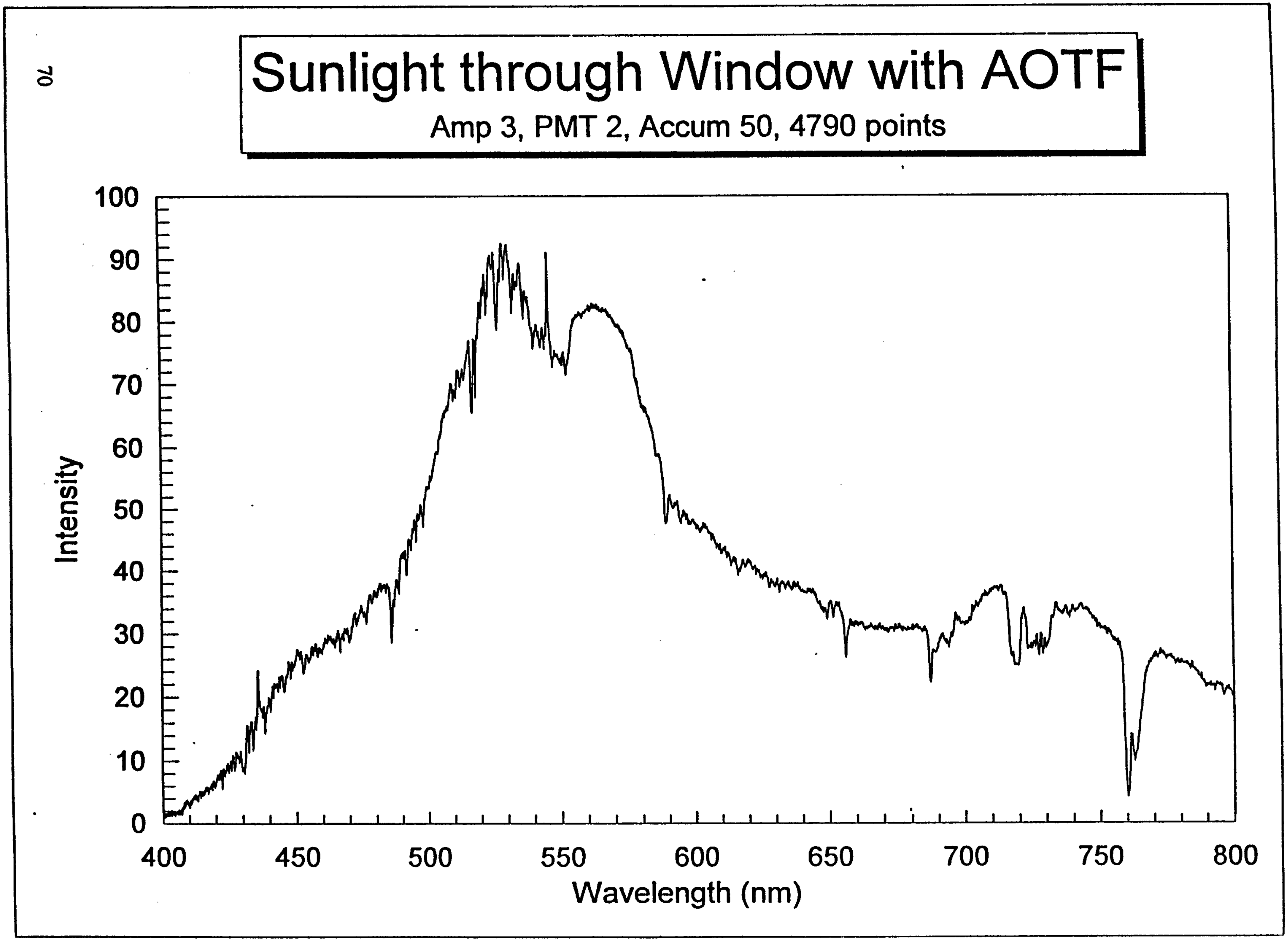
AOTF Spectrometer System




Hg Lamp AOTF Spectra
Amp 1, PMT 1, Accum 1,
max. number of points
Intensity
0
200
400
600
800
1000
1200
1400
300
400
500
600
700
800
Wavelength (nm)


Hg Lamp UV Resolution
Intensity
0
200
400
600
800
1000
1200
1400
1600
311
312
313
314
315
Wavelength (nm)

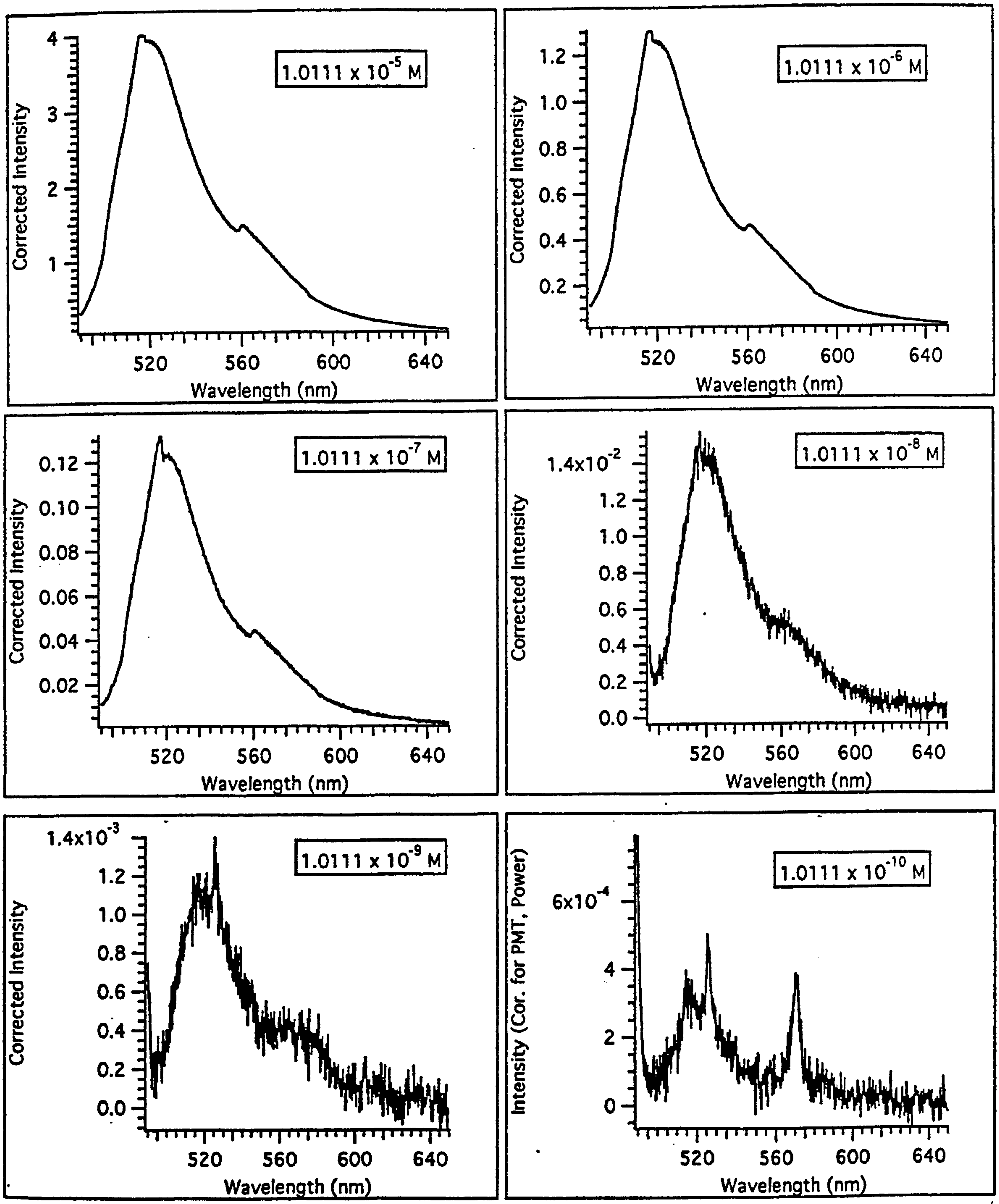

Hg Lamp Visible AOTF Resolution
Intensity
300
250
200
150
100
50
0
574
576
578
580
582
Wavelength (nm)

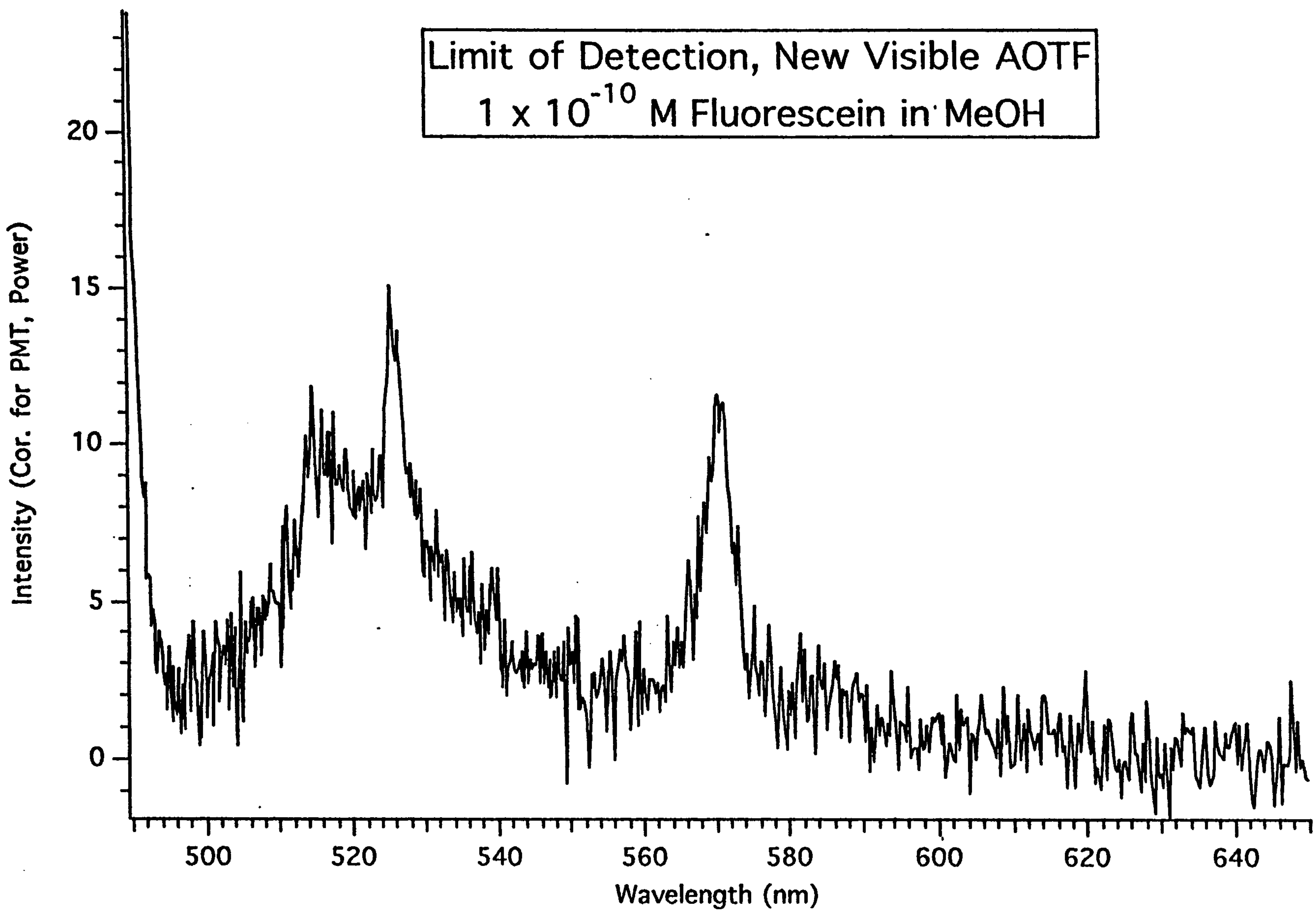


Sunlight through Window with AOTF
Amp 3, PMT 2, Accum 50, 4790 points
Intensity
0
10
20
30
40
50
60
70
80
90
100
400
450
500
550
600
650
700
750
800
Wavelength (nm)

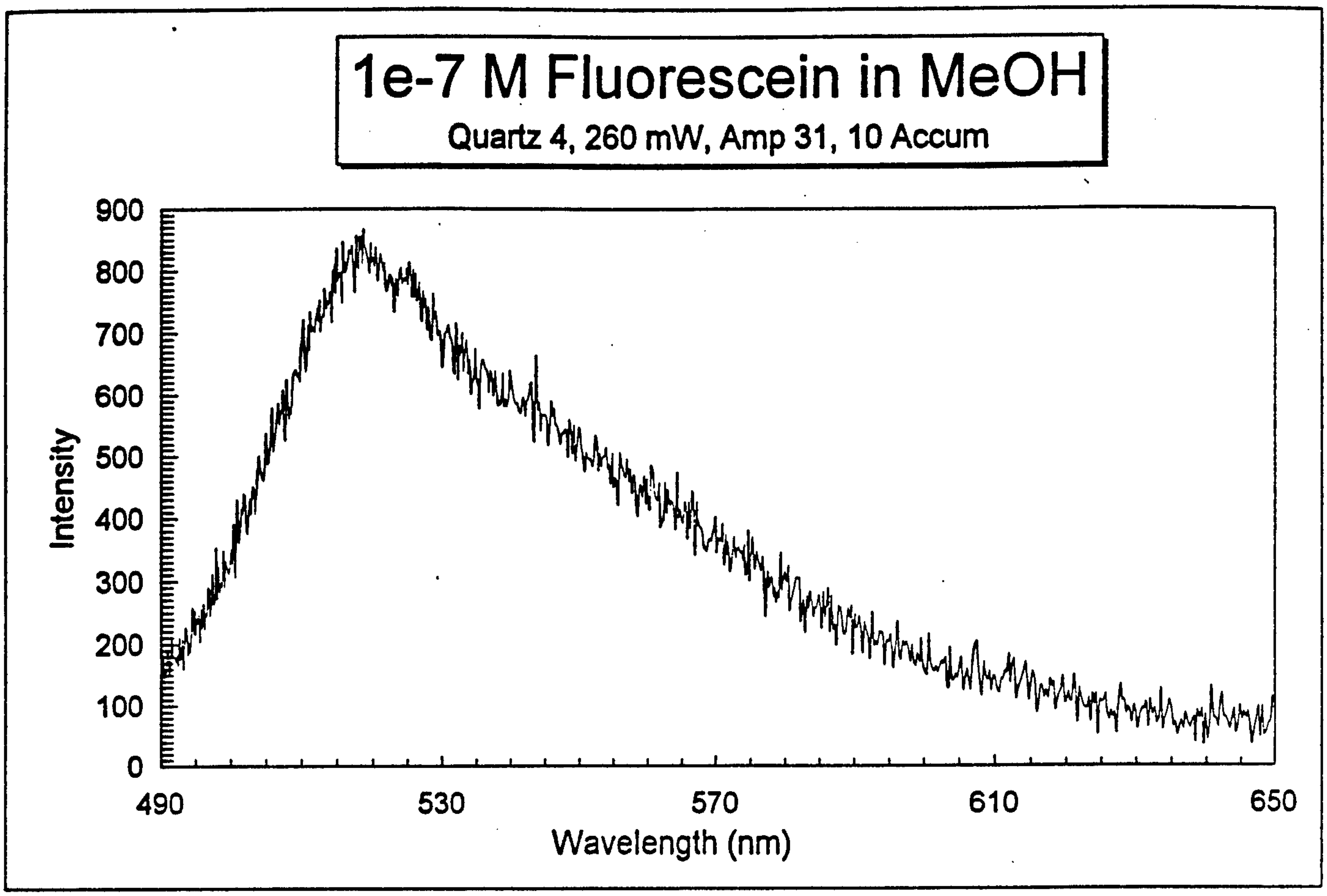
Fluorescein in Methanol Fluorescence

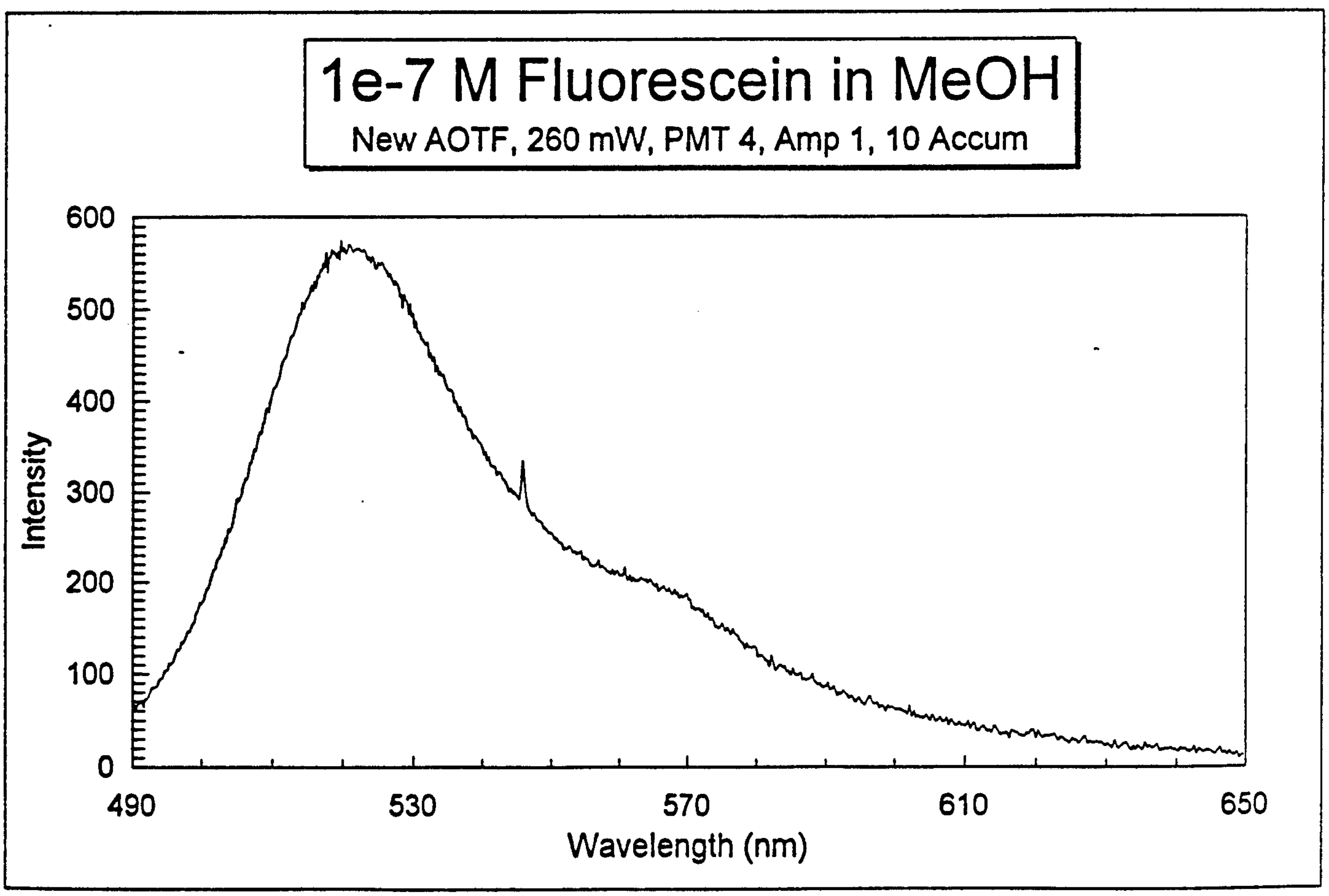
Corrected for laser power and PMT setting

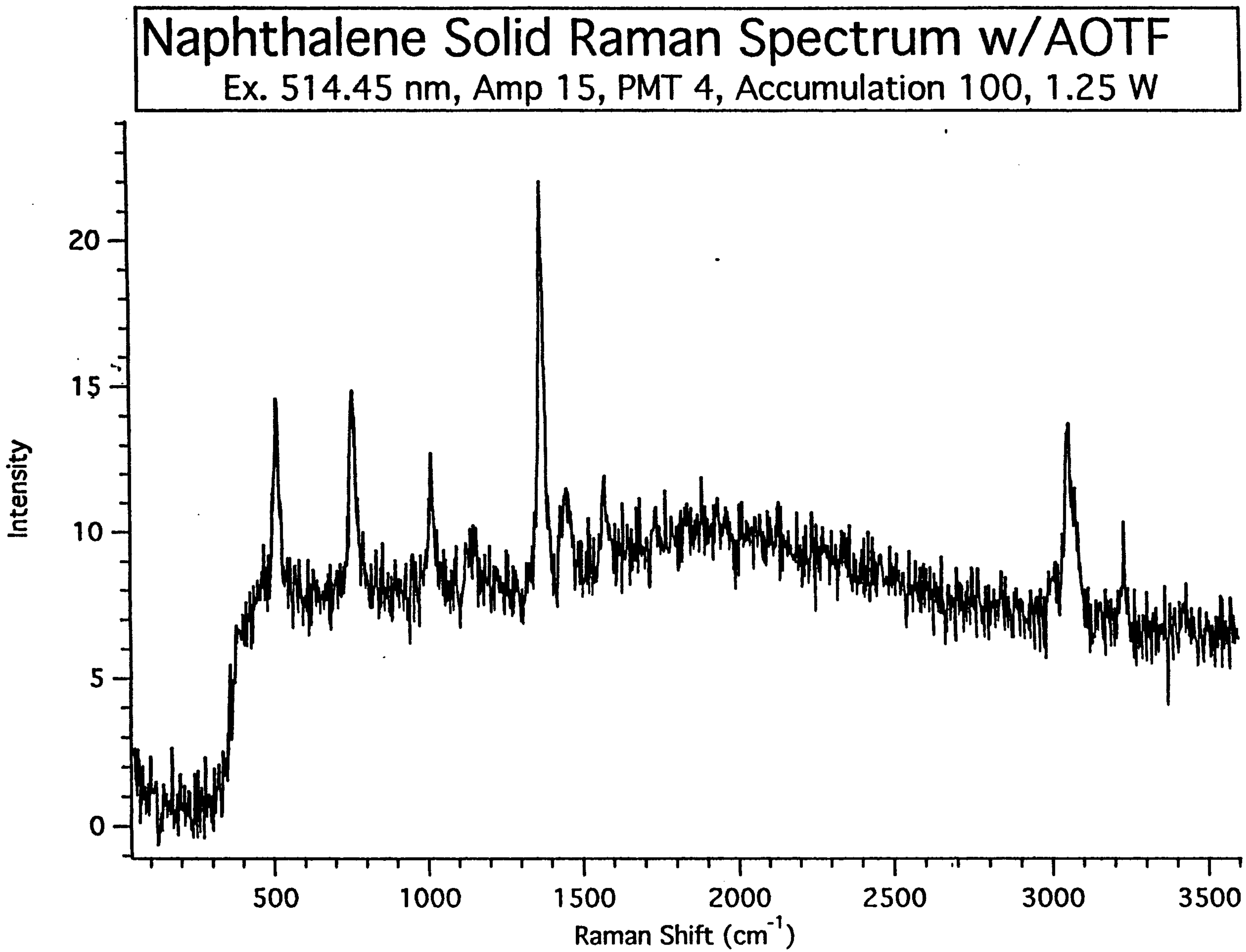



Limit of Detection, New Visible AOTF
1 x 10^{-10} M Fluorescein in MeOH
Intensity (Cor. for PMT, Power)
0
5
10
15
20
500
520
540
560
580
600
620
640
Wavelength (nm)

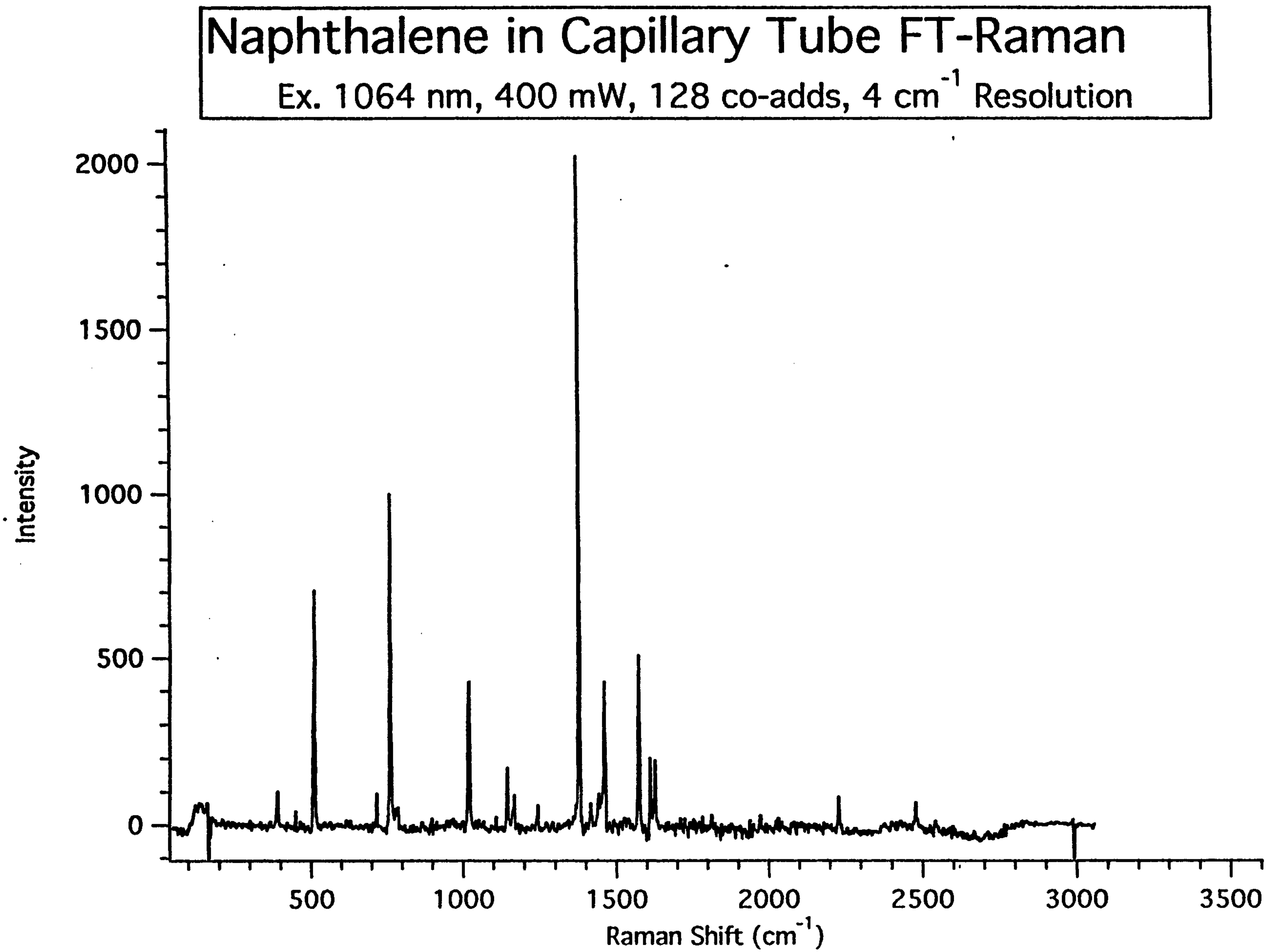
21


1e-7 M Fluorescein in MeOH
Quartz 4, 260 mW, Amp 31, 10 Accum
Intensity
900
800
700
600
500
400
300
200
100
0
490
530
570
610
650
Wavelength (nm)


1e-7 M Fluorescein in MeOH
New AOTF, 260 mW, PMT 4, Amp 1, 10 Accum
Intensity
600
500
400
300
200
100
0
490
530
570
610
650
Wavelength (nm)


Naphthalene Solid Raman Spectrum w/AOTF
Ex. 514.45 nm, Amp 15, PMT 4, Accumulation 100, 1.25 W
Intensity
Raman Shift (cm^{-1})
0
5
10
15
20
500
1000
1500
2000
2500
3000
3500

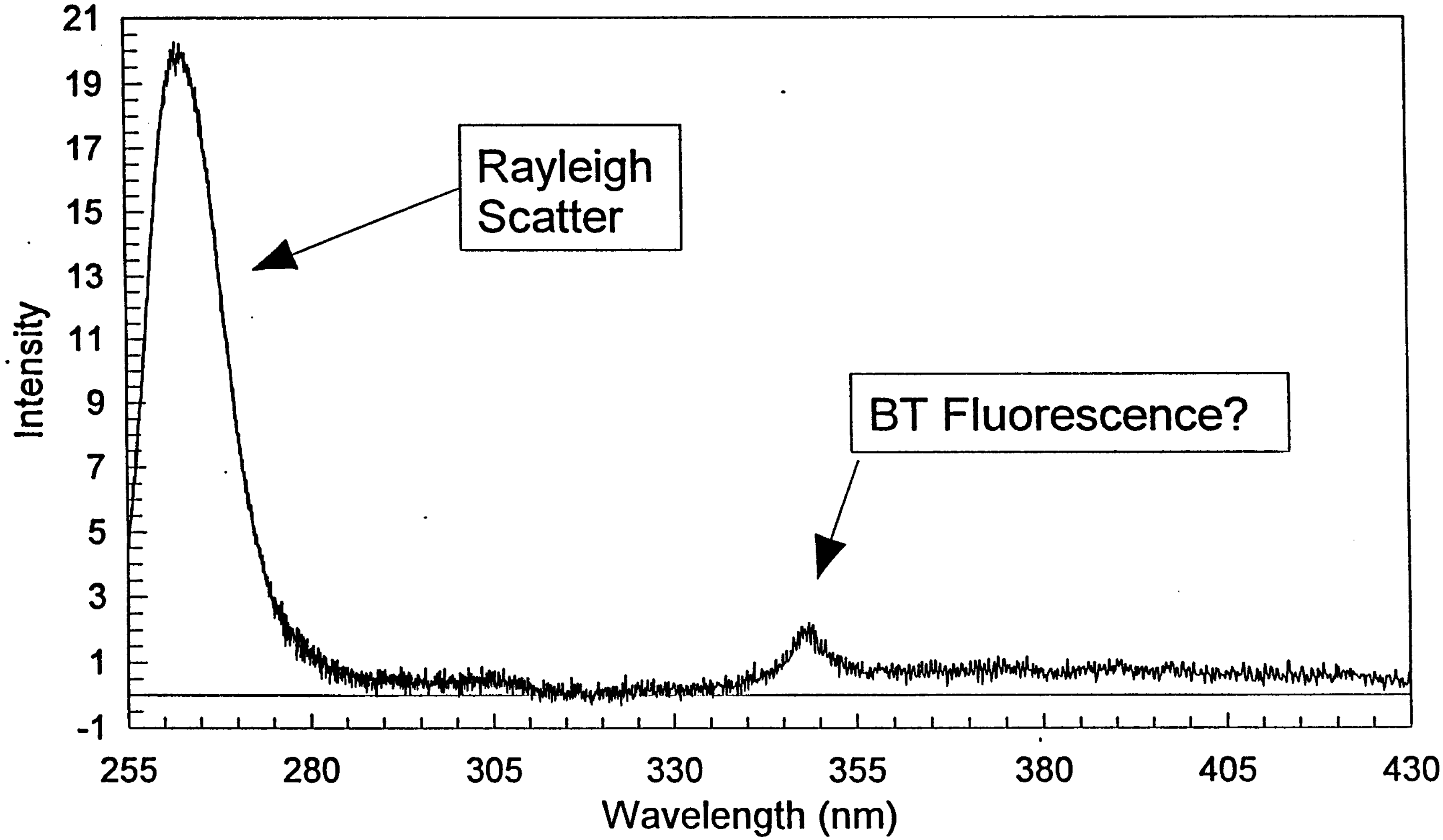
25



Naphthalene in Capillary Tube FT-Raman
Ex. 1064 nm, 400 mW, 128 co-adds, 4 cm-1 Resolution
Intensity
2000
1500
1000
500
0
500
1000
1500
2000
2500
3000
3500
Raman Shift (cm-1)

BT-containing Insecticide in Quartz Cuvette

Ex. 260 nm, Amp 15, PMT 4, Accum 100



SUMMARY

- Characterized Performance for three UV/VIS spectrometers.
- Obtained Results for Fluorescence Measurements.
- Obtained Results for Raman Scattering
- Evaluating Instruments for Stand-off Chem/Bio Detection.
- Mid-IR AOTF being Developed.
- Imaging Experiments Planned.
- Polarization Experiments Planned.
- Fire Sensing Proposed.

FACTORS AFFECTING AOTF IMAGE QUALITY

L.J Denes, Boris Kaminsky, M. Gottlieb and P. Metes

Carnegie-Mellon Research Institute
Pittsburgh, Pennsylvania

This work was supported under U.S. Army SBIR subcontract, No. DAAB07-93-C-0005, and U.S. Navy contract N00014-95-1-0591

Image Blur Relation to θ_I and L

For small values of $n_i - n_d$ and $\Theta_i - \Theta_d$, the non-critical phase matching (NPM) condition can be approximated as

$$\lambda_0 / \Lambda = n_0 (\Theta_i - \Theta_d)$$

The usual NPM aaproximation for tuning is

$$\lambda_0 / \Lambda = \Delta n (\sin^4\Theta_i + \sin^2 2\Theta_i)^{1/2}$$

so that an approximation to the beamspread is

$$\Delta\Theta_d / \Delta\lambda = (\Delta n / n_o \lambda_o)(\sin^4\Theta_i + \sin^2 2\Theta_i)^{1/2}$$

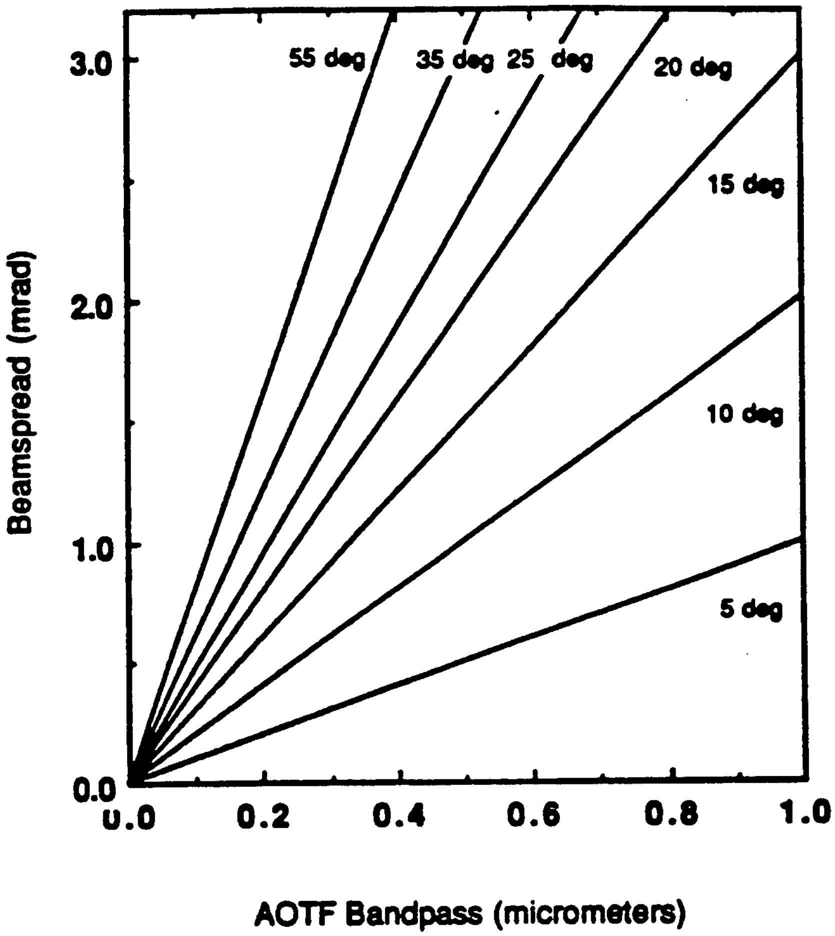
This approximation agrees well with the exact calculations.

It is straightforward to recast the dependence on the transducer length by substituting for $\Delta\lambda$

$$\Delta\lambda = 1.8\pi\lambda^2 / (\Delta n \cdot L \sin^2\Theta_i)$$

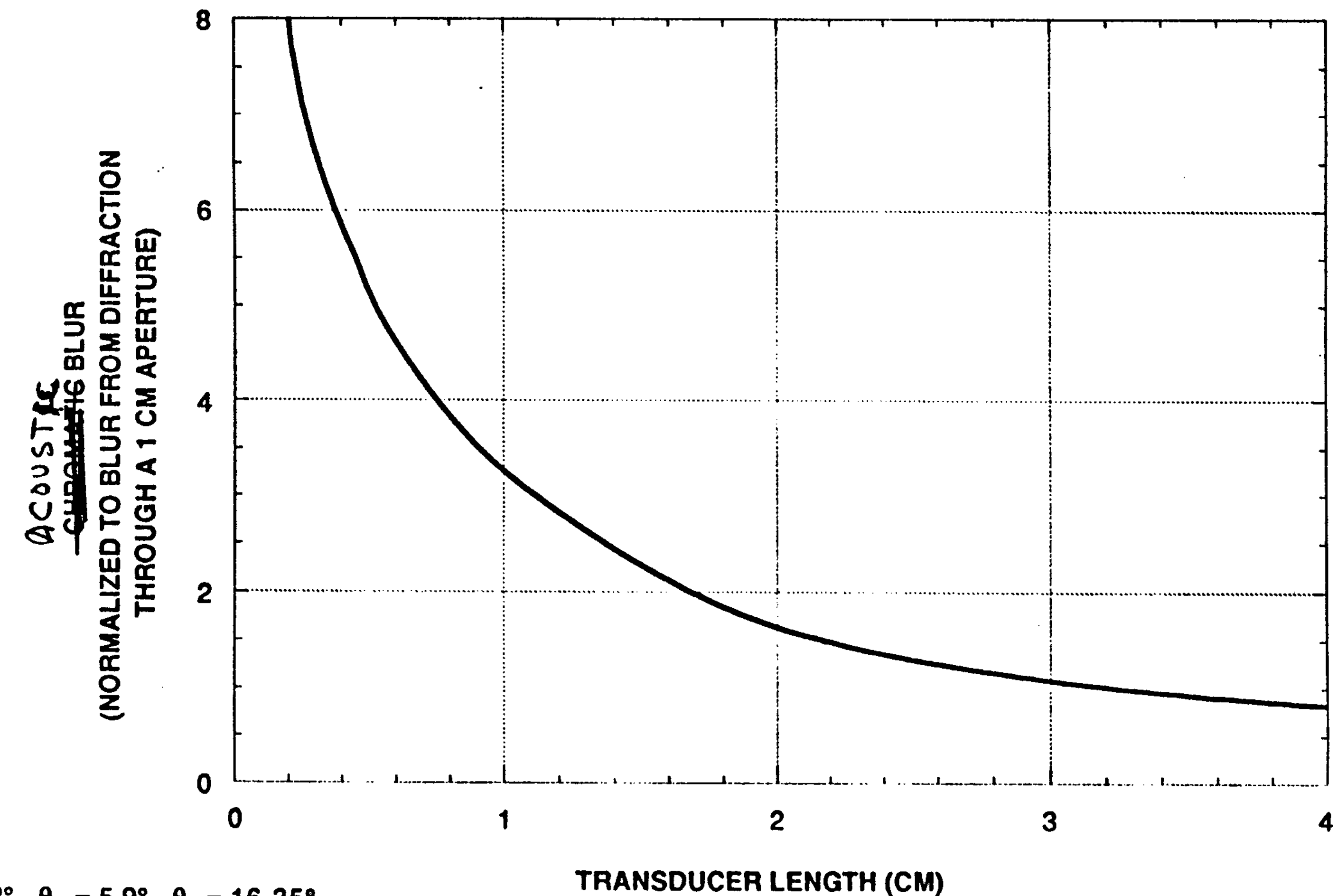
to obtain

$$\Delta\Theta_d = ((\sin^4\Theta_i + \sin^2 2\Theta_i)^{1/2} / \sin^2\theta_i)(1.8\pi\lambda)/nL$$

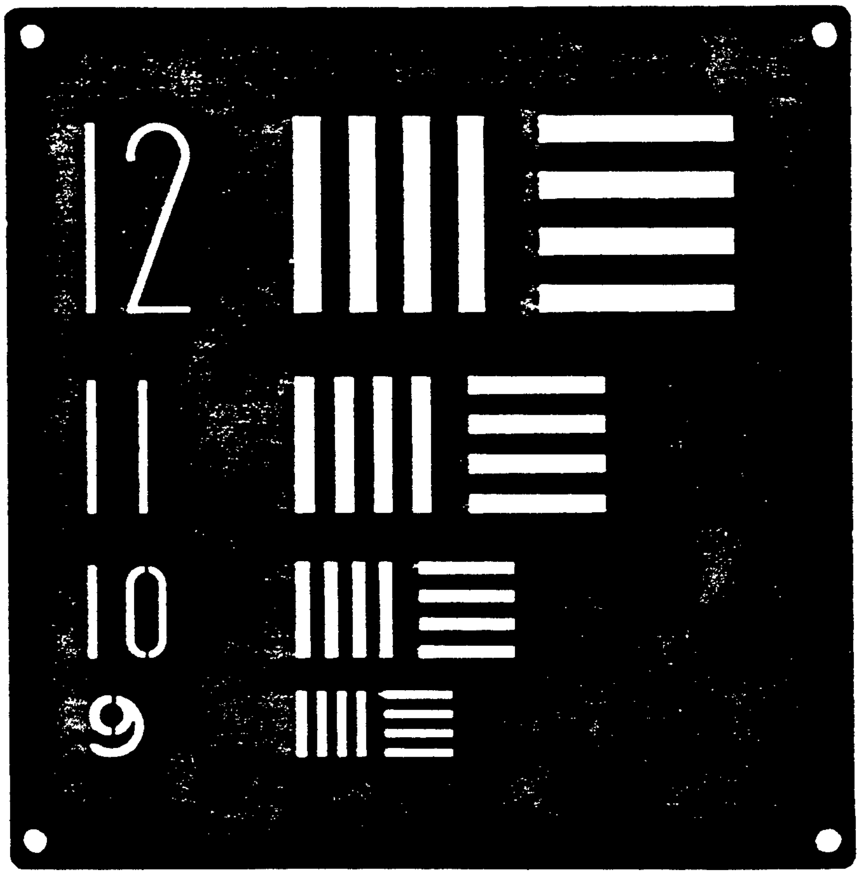


Calculated internal beam spread due to the filter bandpass for various noncollinear TAS AOTF configurations.

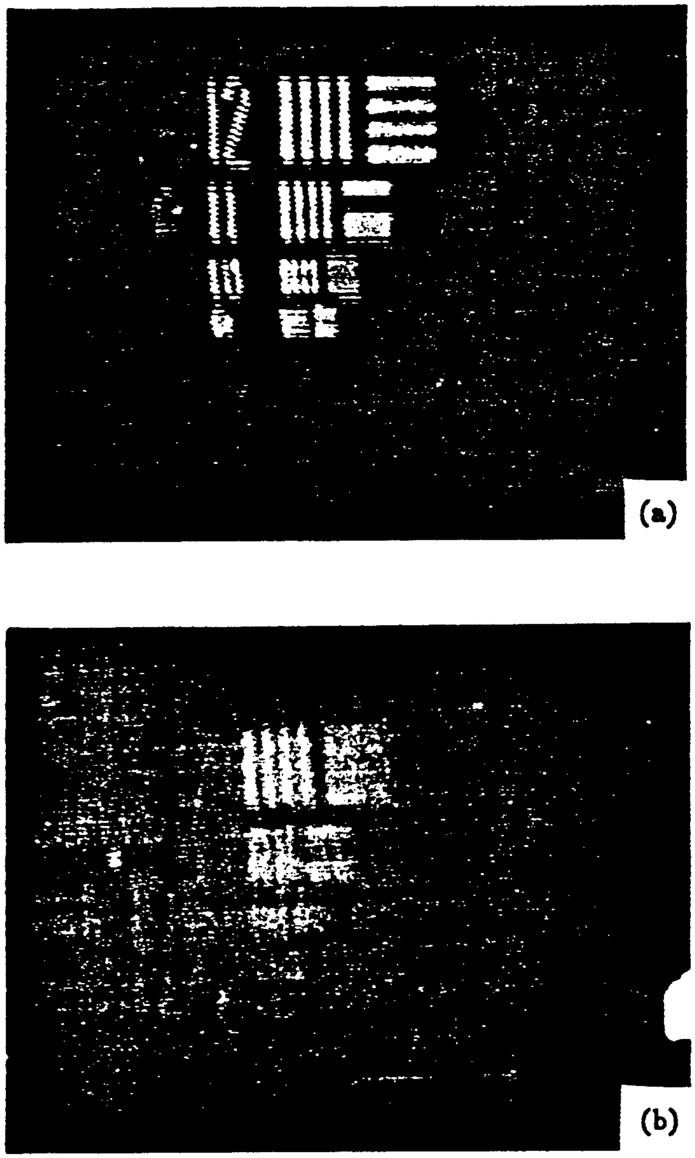
ACOUSTIC BLUR IS MINIMIZED BY PROPER CHOICE
OF TRANSDUCER LENGTH



$\theta_i = 12°$, $\theta_a = 5.9°$, $\theta_f = 16.35°$



Infrared resolution target for imaging system.



(a)

(b)

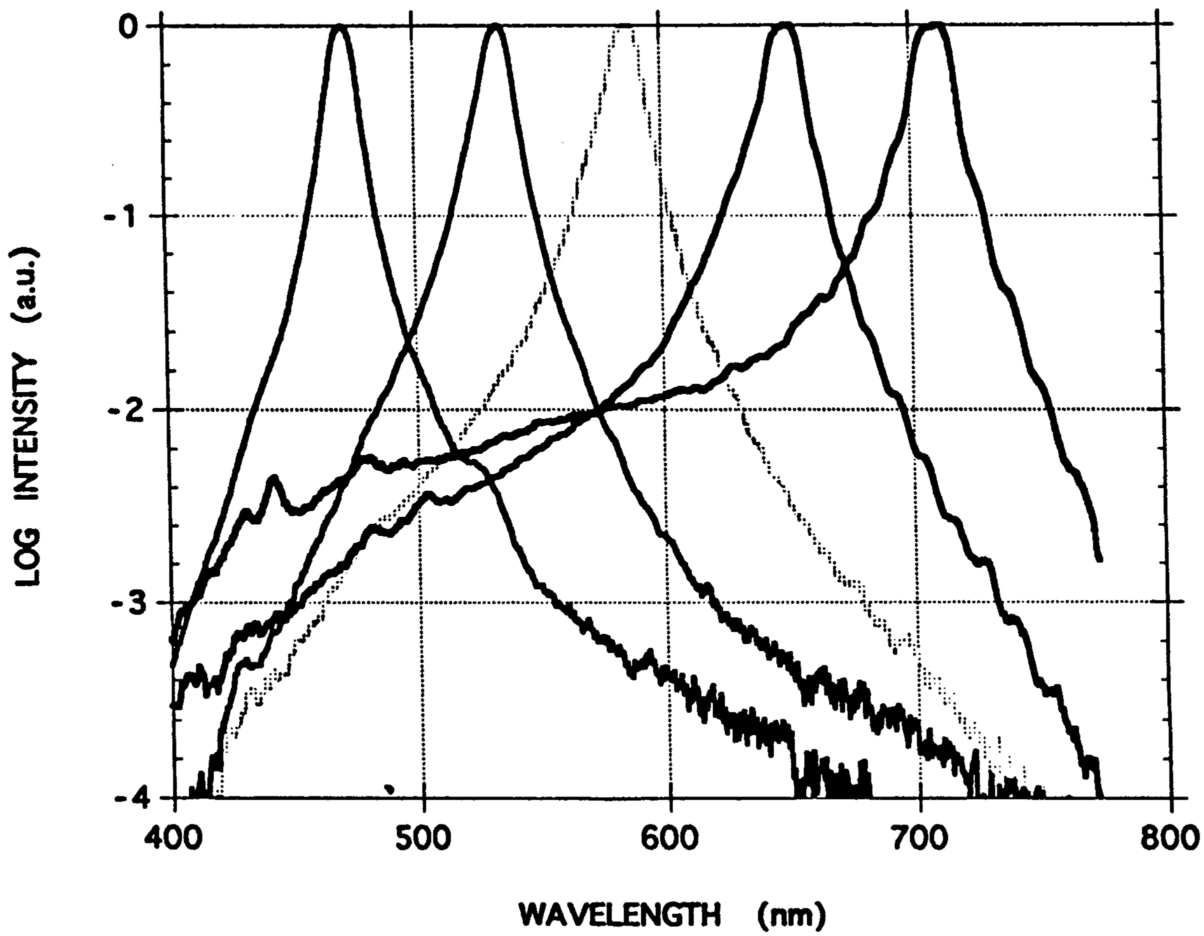
Figure 5. Infrared target image (a) without AOTF, and (b) with noncollinear AOTF.

AOTF-1 Parameters

Θ_I = 12 degrees
$\Delta\theta_I$ = 6.5 degrees (ext)
Θ_a = 5.9 degrees

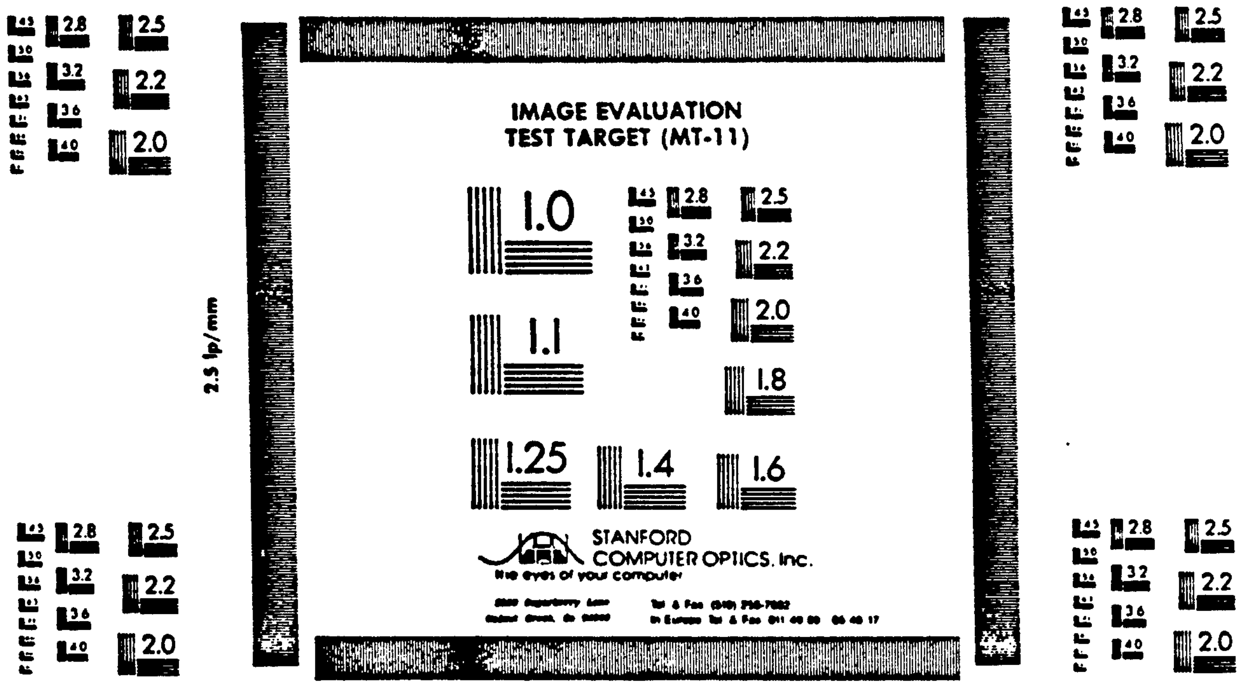
L_1 = 0.33 cm
L_2 = 0.66 cm
L_3 = 1.32 cm
L_4 = 2.32 cm

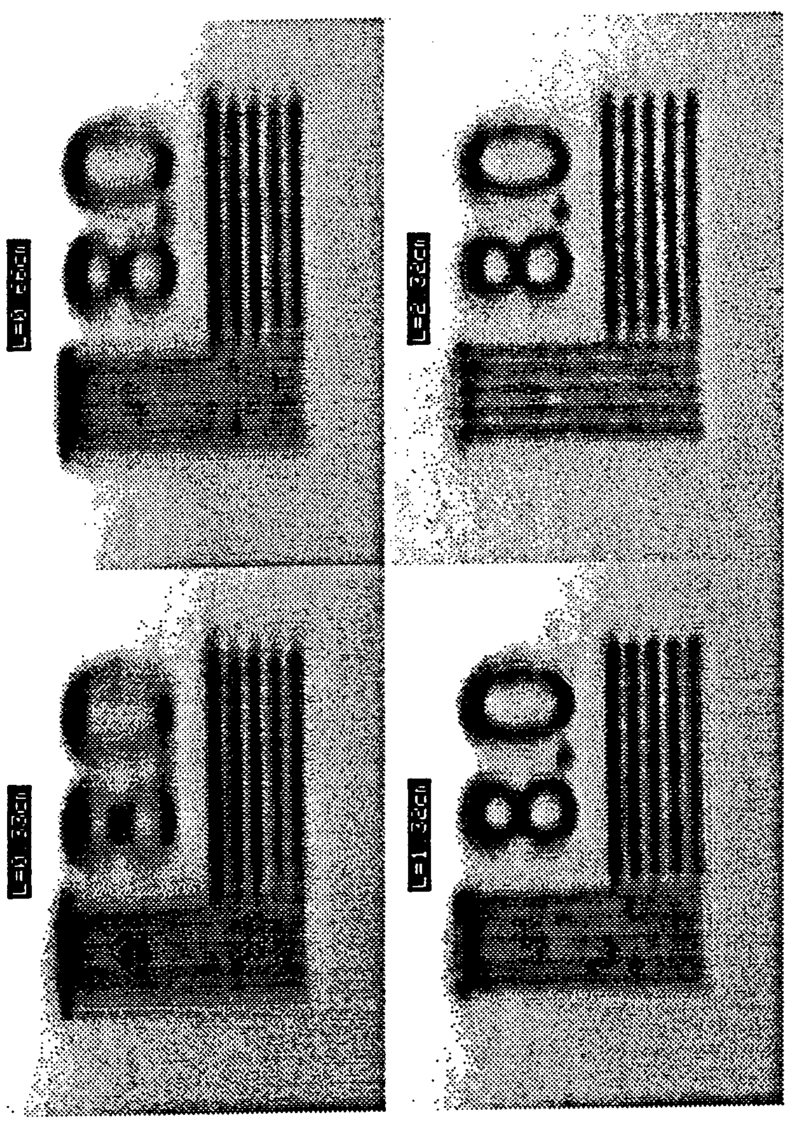
$\Delta\lambda/\lambda$ = .01 (for L = 2.32 cm)


0
-1
-2
-3
-4
LOG INTENSITY (a.u.)
400
500
600
700
800
WAVELENGTH (nm)

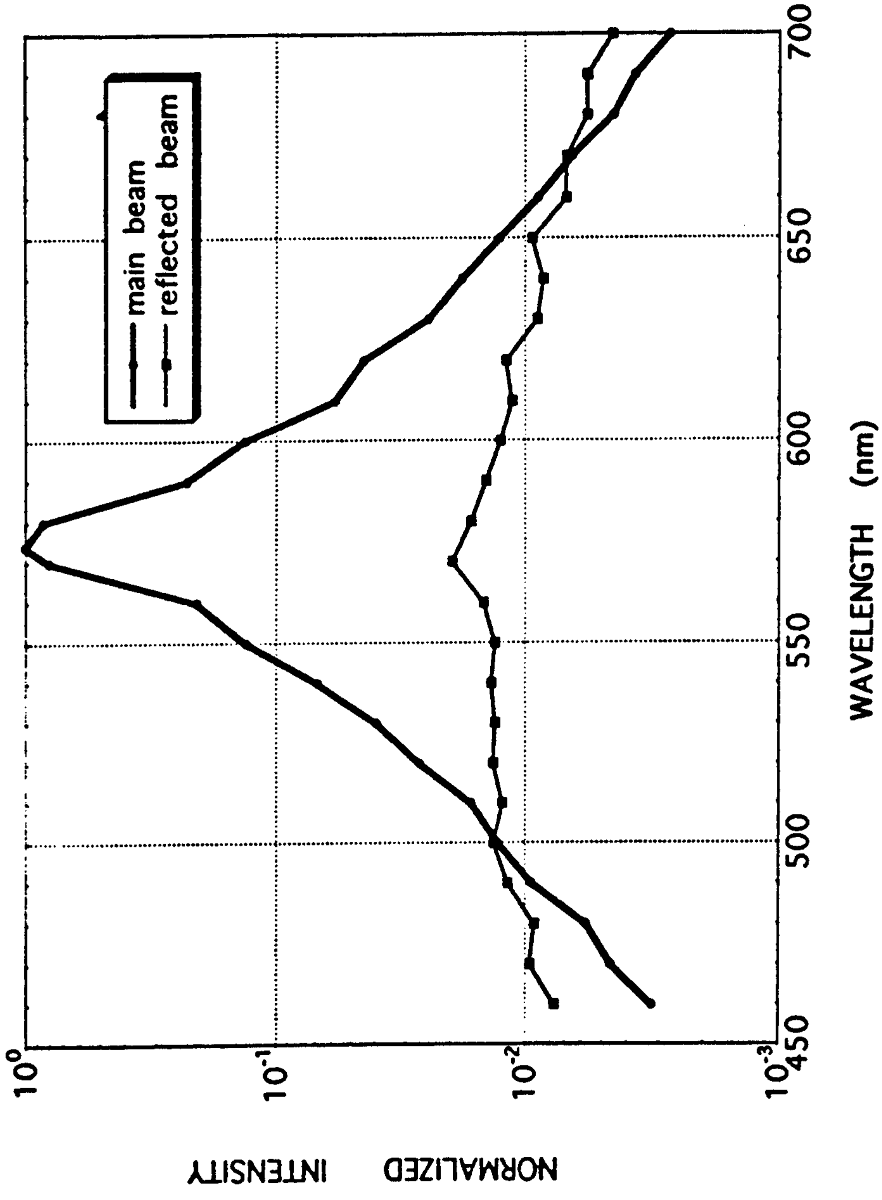
CARNEGIE
MELLON
RESEARCH
INSTITUTE

A division of Carnegie Mellon University





CONTRIBUTIONS TO AOTF BACKGROUND: PRIMARY ACOUSTIC BEAM VS REFLECTED ACOUSTIC BEAM



Scattering

The ratio of scattered light intensity to diffracted image signal is approximately

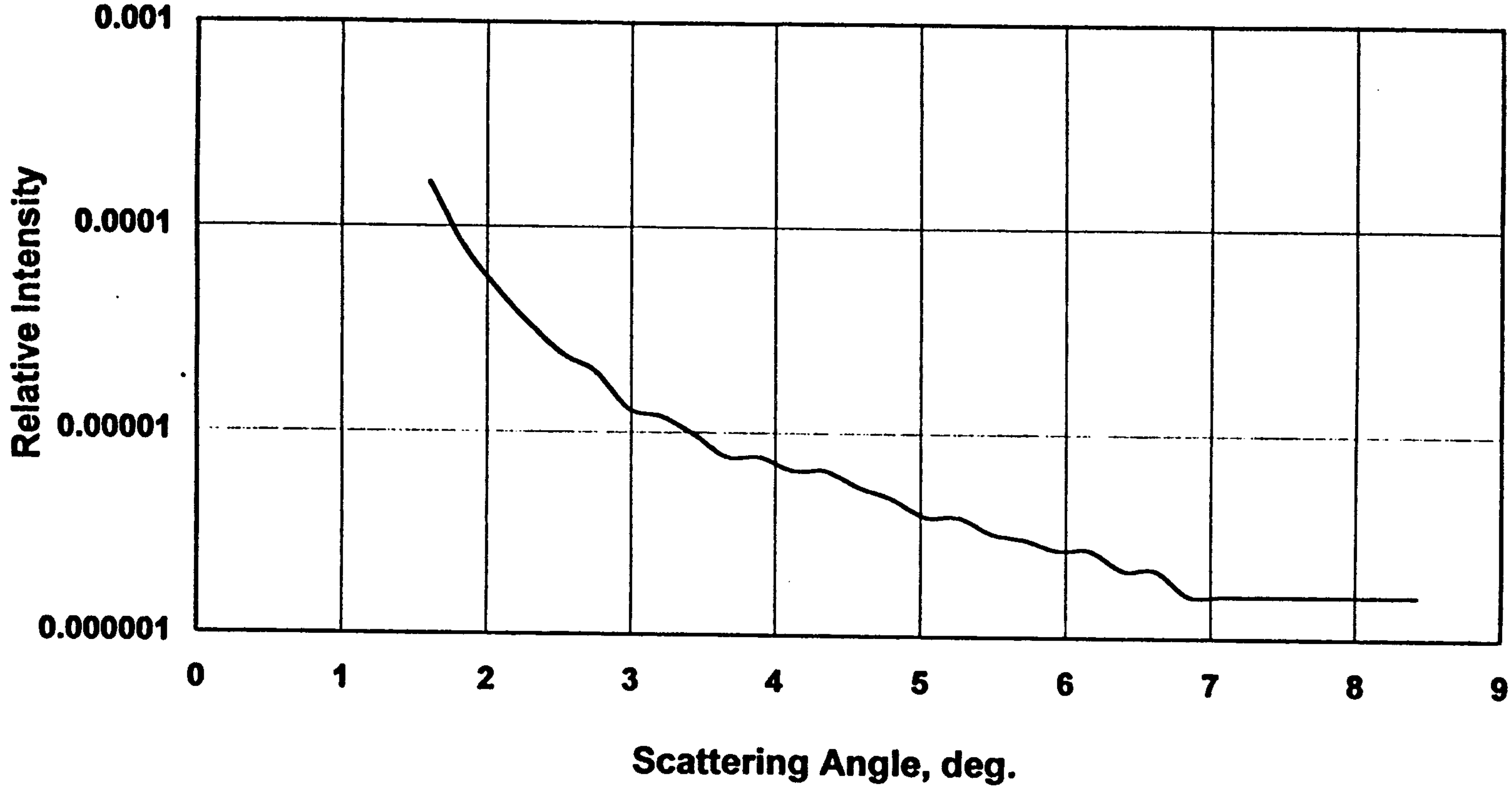
$$I_{scat} / I_{image} = S \cos^2 \phi (\Delta\lambda / \delta\lambda) + (p\ \eta)$$

where:

S = scattering coefficient
ϕ = scattering angle
$\delta\lambda$ = AOTF resolution
$\Delta\lambda$ = spectral range of light source and detector
p = polarization loss, at least 50%
η = AOTF efficiency

For a typical AOTF design, $S \sim 10^{-5}$, $(\Delta\lambda/\delta\lambda) = 100$, $p = 0.5$, and $\eta = 0.5$, and $\cos^2 \phi \sim 1$, so that the estimated scattered light intensity is about 24 dB below the image signal.

LASER LIGHT SCATTERING FROM TYPICAL AOTF



Multi-spectral Imaging

Where are we going ?

Carnegie Mellon

Multi-spectral Imaging

MURI Program ONR

Targets

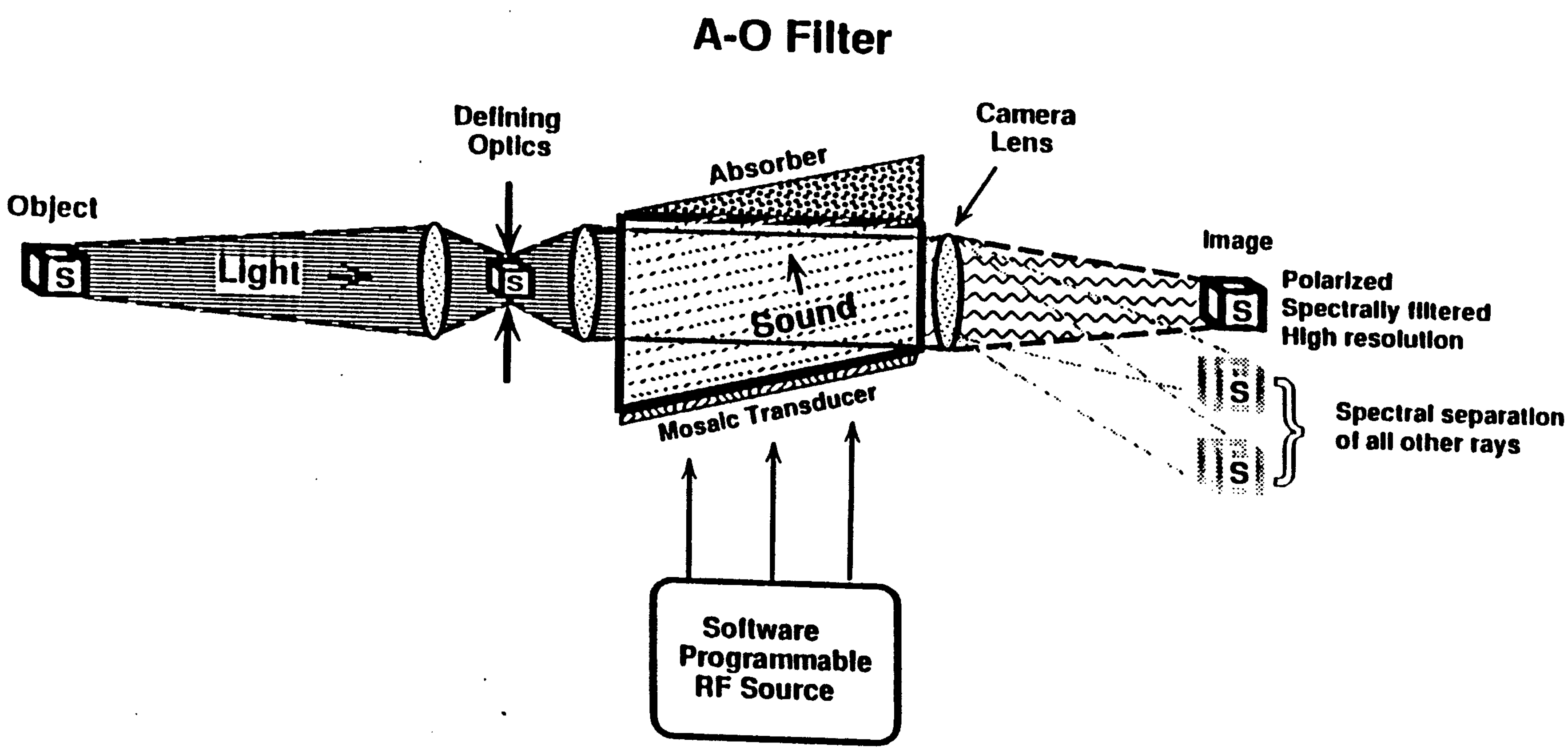
• Wavelength tunability:	1 -> 2 Octaves
• Field of view	2-12°
• Spectral resolution:	10-20 nm, $\Delta\lambda/\lambda=(0.1-1)\%$
• Spatial resolution:	<1 μradian
• Background:	Limited by camera noise

Multi-spectral Imaging

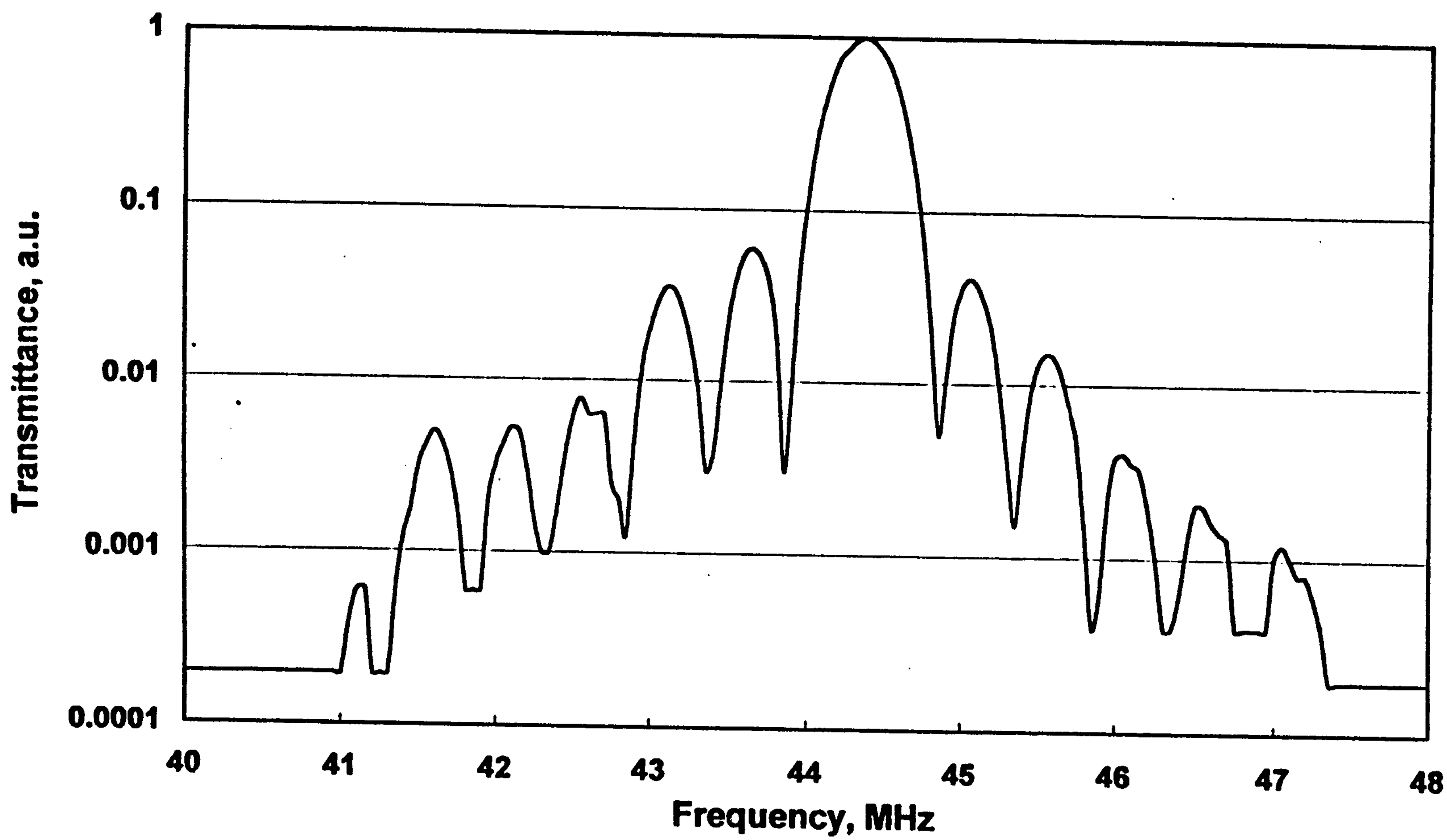
Critical Parameters

- Optical system configuration
  - AOTF (design & fabrication)
- Suppression of:
  - Blur
  - Ghost images
  - Broadband background
- Transducer design
- Transducer fabrication
- AR coatings

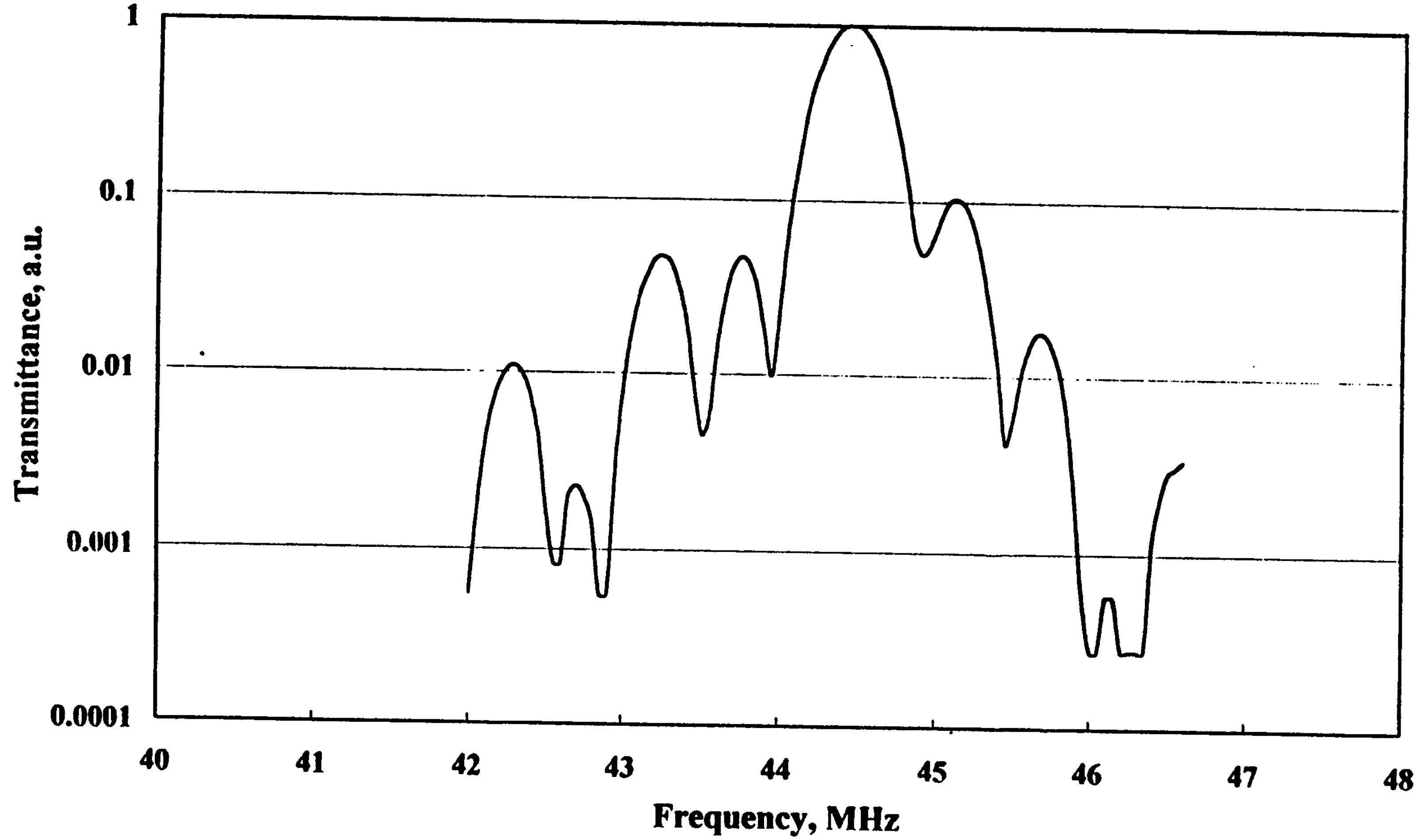
Imaging A-O Spectrometer



SPECTRAL RESOLUTION OF NEOS 4-3-P-1 AOTF



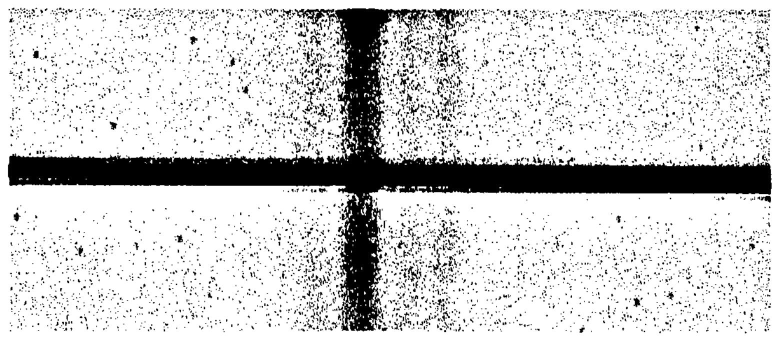
SPECTRAL RESOLUTION OF NEOS 4-3-S-1 AOTF

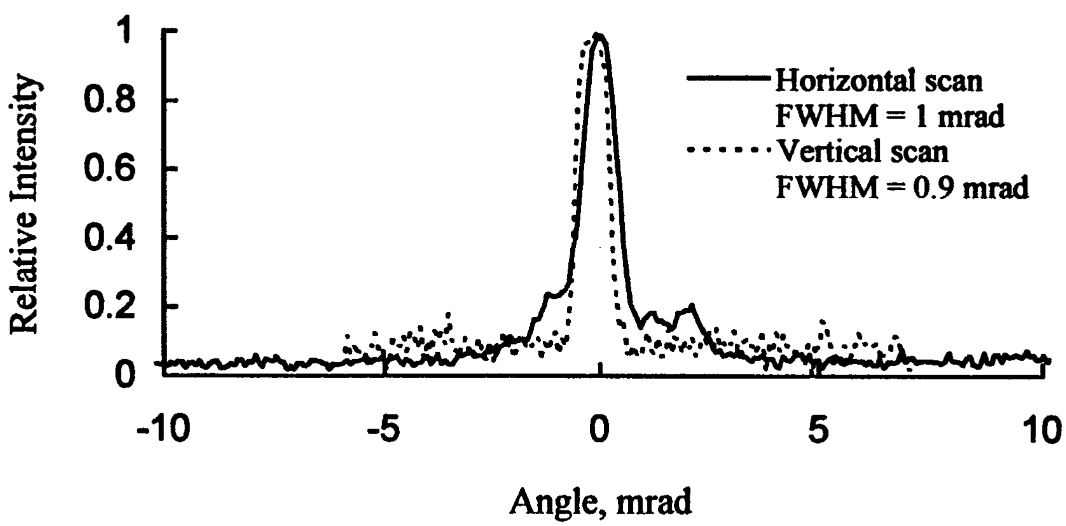


Carnegie Mellon

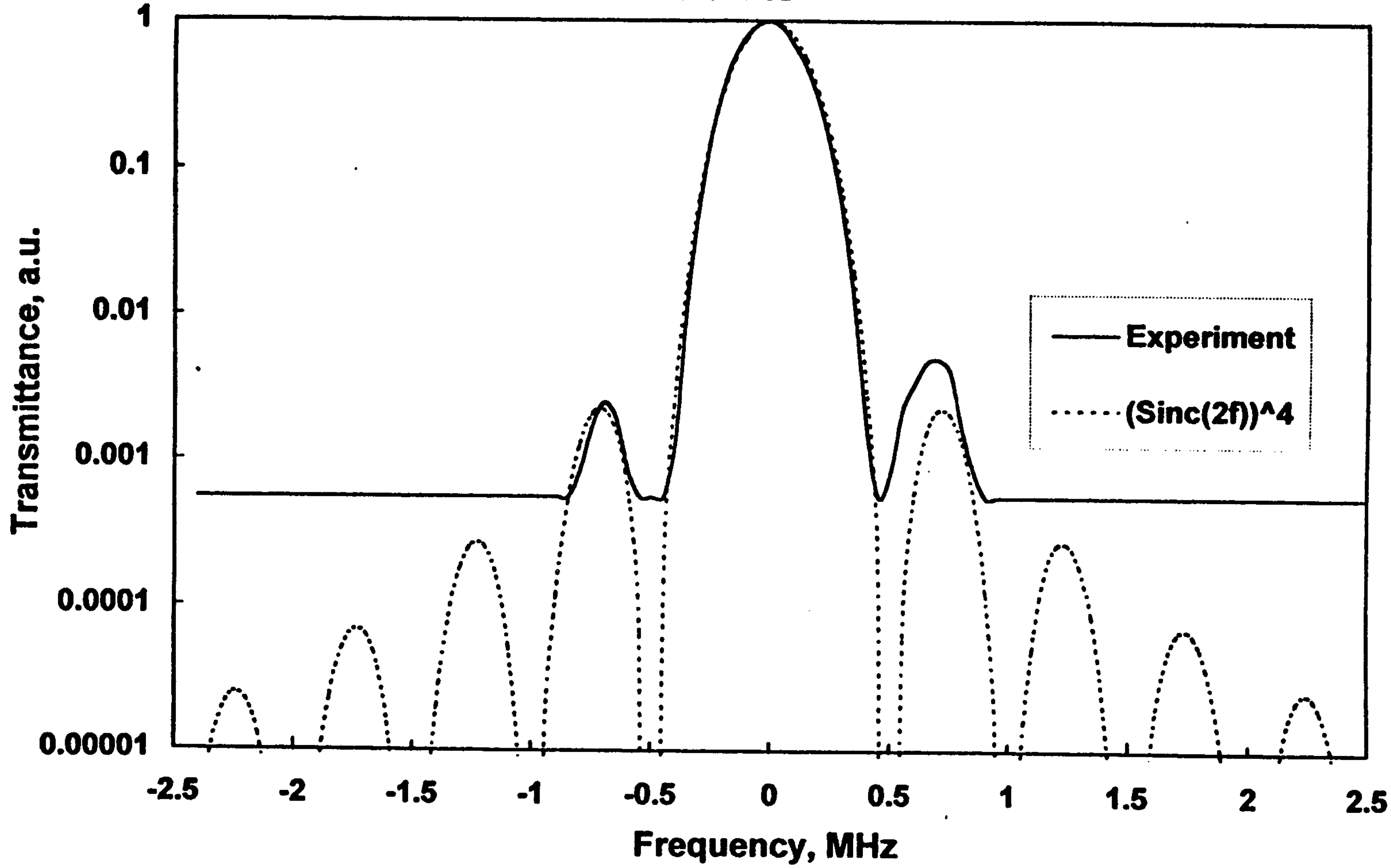
Multi-spectral Imaging

MURI Program

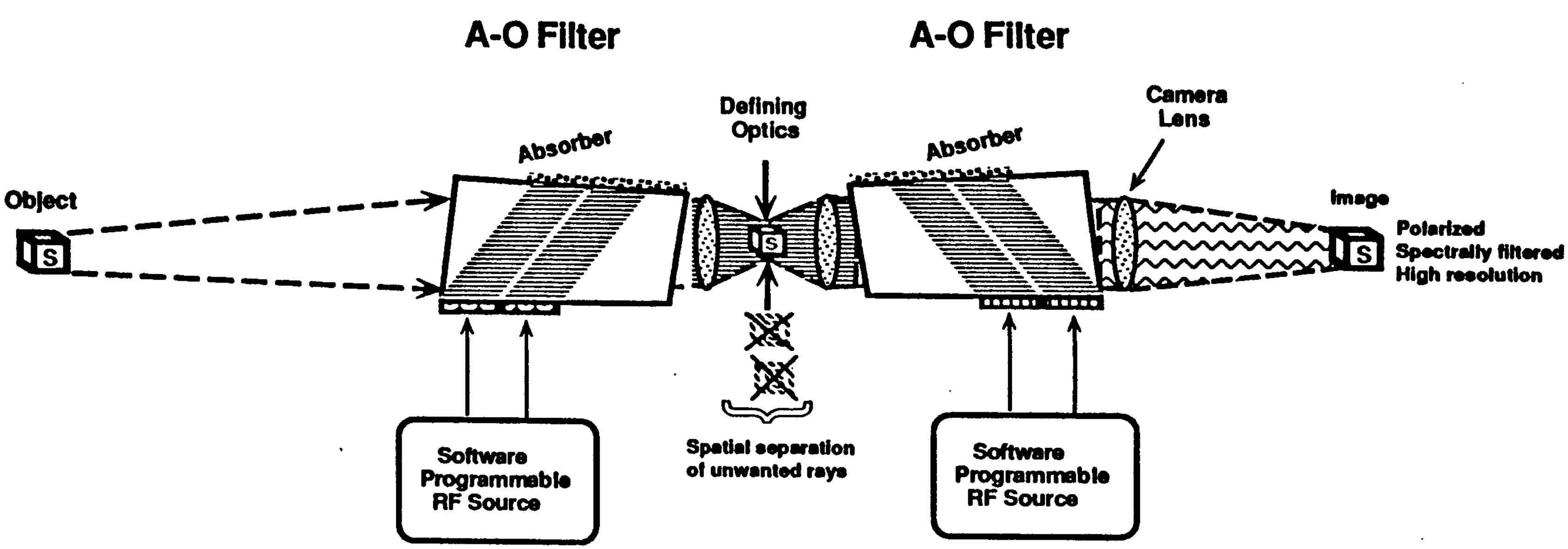




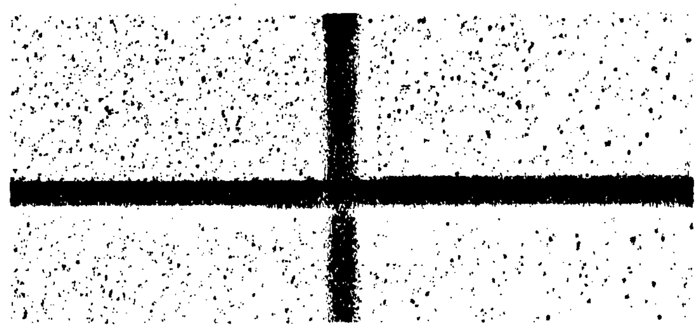
SPECTRAL RESOLUTION OF NEOS 4-3-S-1 AND 4-3-P-1 AOTF IN SERIES

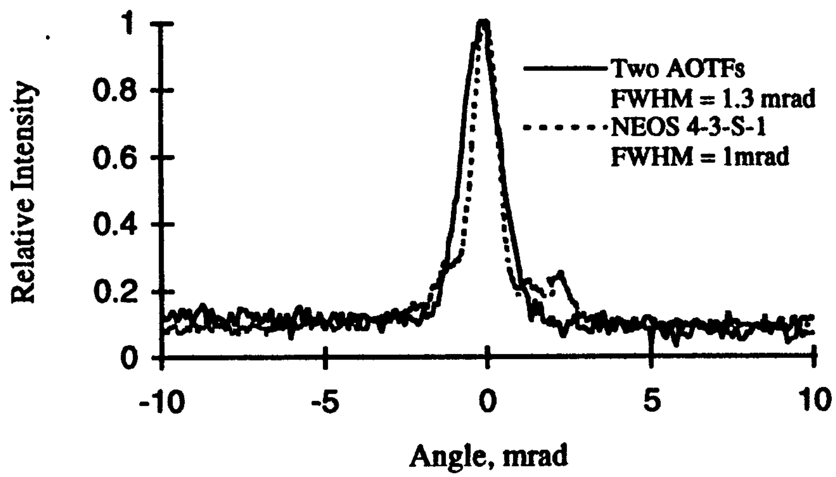


Second Generation
Imaging A-O Spectrometer



Multi-spectral Imaging





Multi-spectral Imaging

Conclusions

- Image quality is limited by blur, side lobes and broadband scattering
- Our two AOTF configuration offers a solution to the above problems
- Present work was performed in the VIS & NIR,
  Future work is planned to include the Mid & Far IR

An AOTF Camera for Multispectral Imaging

S. Simizu, R. T. Obermyer, C. J. Thong, M. J. Uschak, and S. G. Sankar
Advanced Materials Corporation
700 Technology Drive, Pittsburgh, PA 15230

and

L. J. Denes, D. A. Purta, and M. Gottlieb
Carnegie Mellon Research Institute
Pittsburgh, PA 15230

*** Supported by the US Army under Contract No. DAAB07-95-C-M042**

Overview

1. Camera System

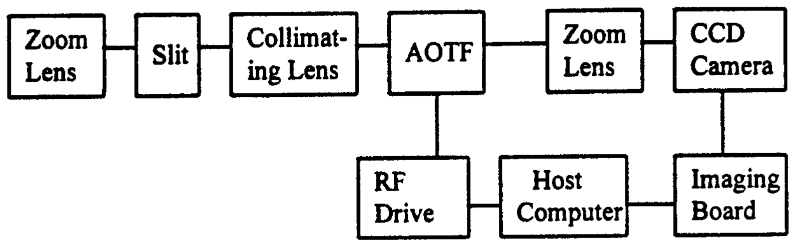
    Defining Optics
    AOTF Design
    Camera/Imaging Hardware
    RF Drive

2. System Performance

    Filter Characteristics
    Blur/Background

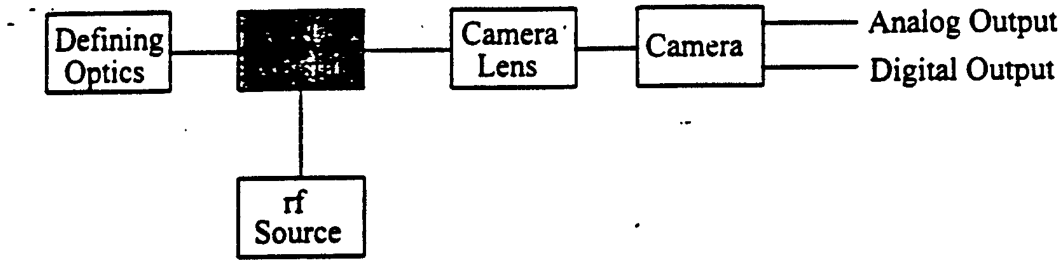
3. Target Identification

    Image Pre-processing by AOTF
    Processing Speed



A block diagram of the AOTF camera system

Advanced Material Corp.

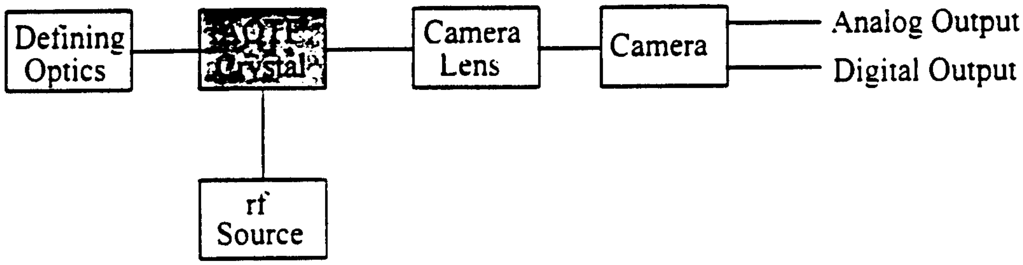


Defining Optics

- 8 -- 80 mm motorized (focus, zoom, iris) zoom lens
- Rectangular stop to match 2.5° separation angle of the AOTF
- 50 mm collimation lens
- FOV 1.6° -- 15.6°

AOTF Crystal

- AMC/CMRI design
- Three parallel transducers
- Vertical diffraction (CCD less sensitive to vertical blur)

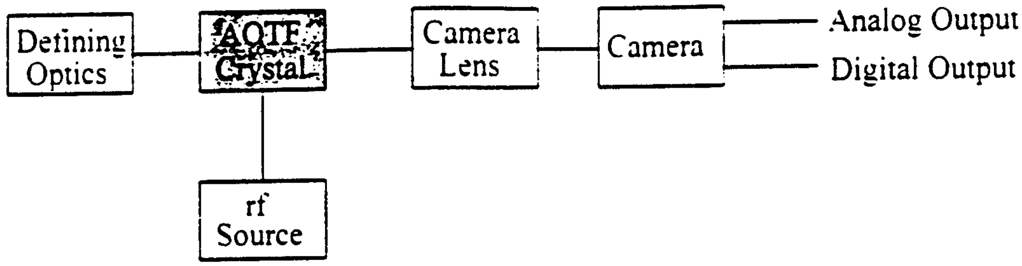


R.F. Source

- Tektronix AWG2040 arbitrary waveform generator
- 1.024 GS/s
- 1 Meg of waveform memory
- 8 bits output
- 2 V maximum amplitude

Camera Lens

- 60 -- 300 mm zoom lens
- 135 mm present position

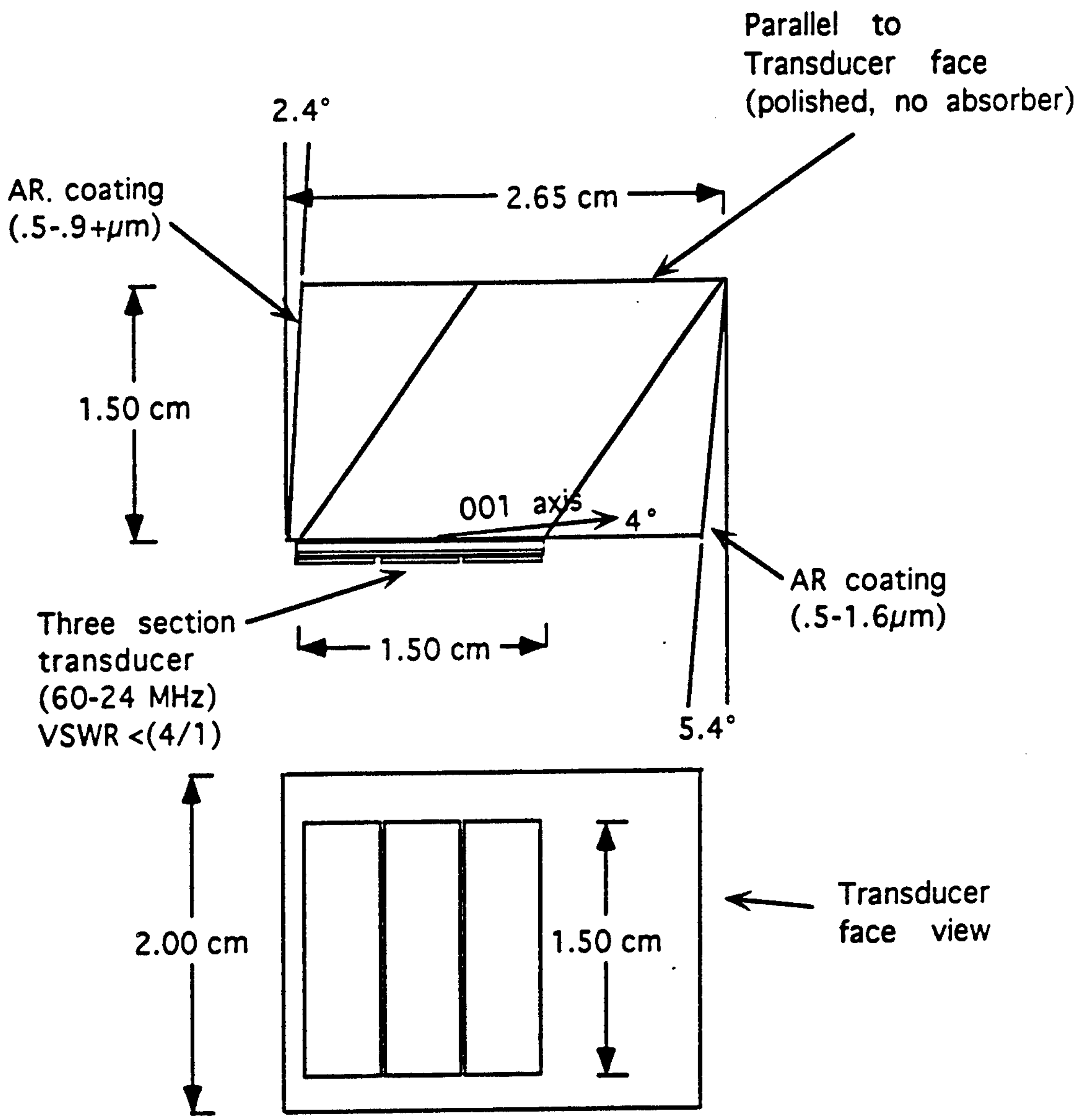


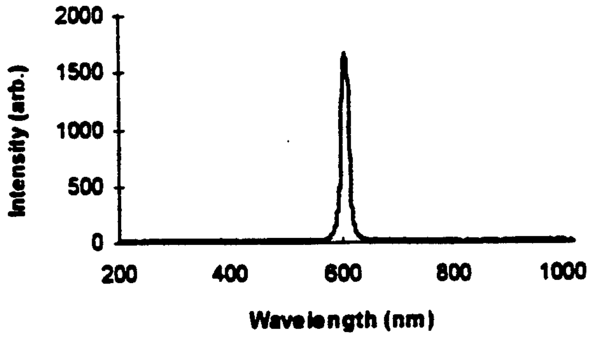
Camera

- DVC Model DVC-10
- SNR of 62 db at 0.5 lux
- Spectral range of 0.45 -- 1.0 μ
- 755 x 484 pixels
- Simultaneous 10 bit parallel and analog video
- Real time capability of 30 frames per second
- On camera digitization

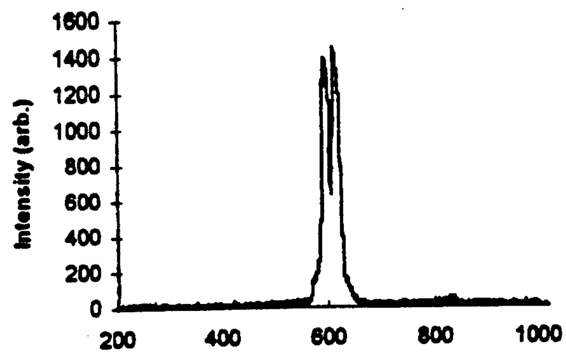
Nominal Specifications for
TeO2 Acousto-optical tunable filter

Designed by:
Louis J. Denes and Milt Gottlieb
Carnegie Mellon Research Institute

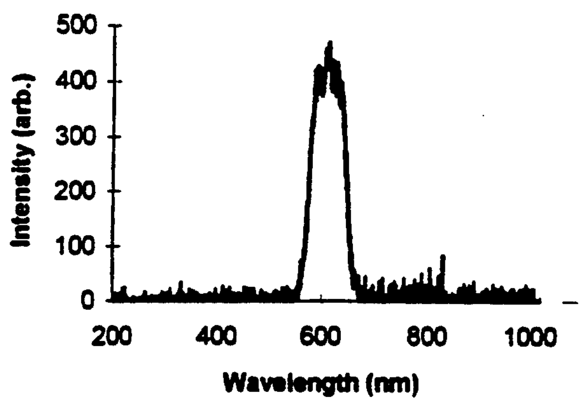




(a)

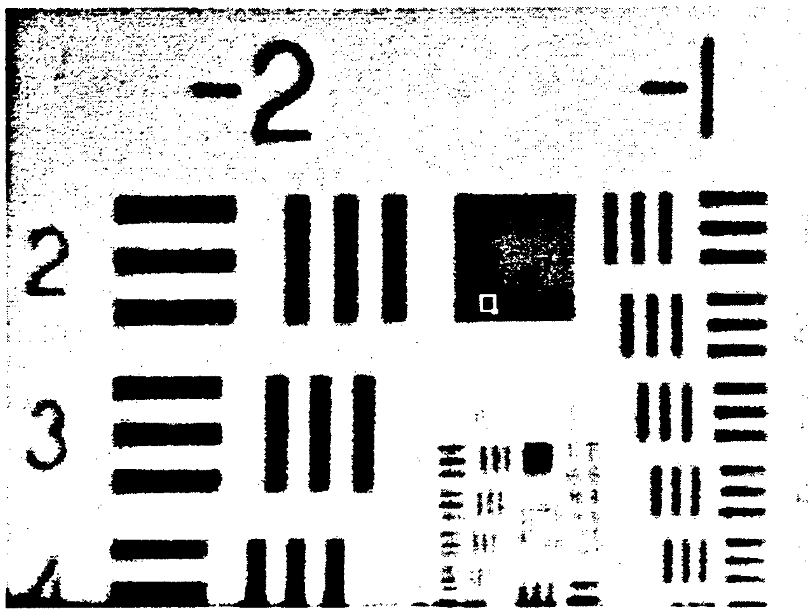


(b)

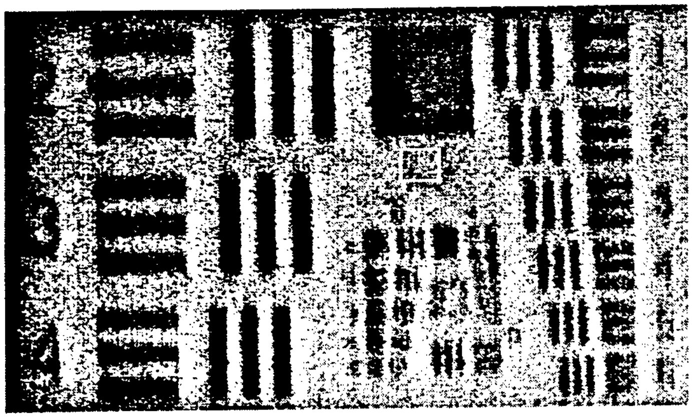


(c)

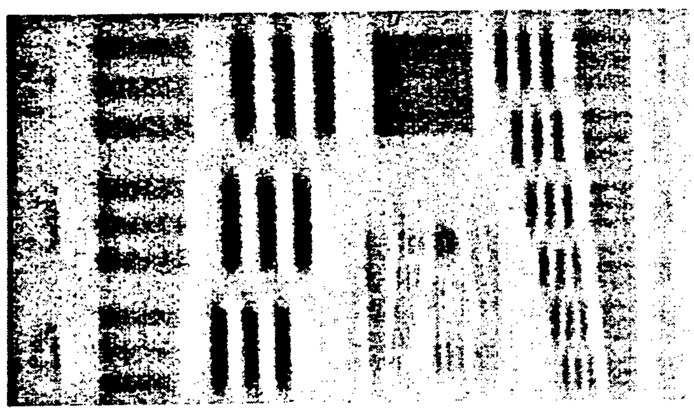
Fig. 6. Different characteristics of AOTF for three RF driving waveforms:
(a) Driven by a single sinusoidal wave at 63.57 MHz;
(b) Driven by a combination of two sinusoidal waves at 60.85 MHz and 63.57 MHz;
(c) Driven by a spread RF spectrum in the range of 59.03 MHz to 67.21 MHz.



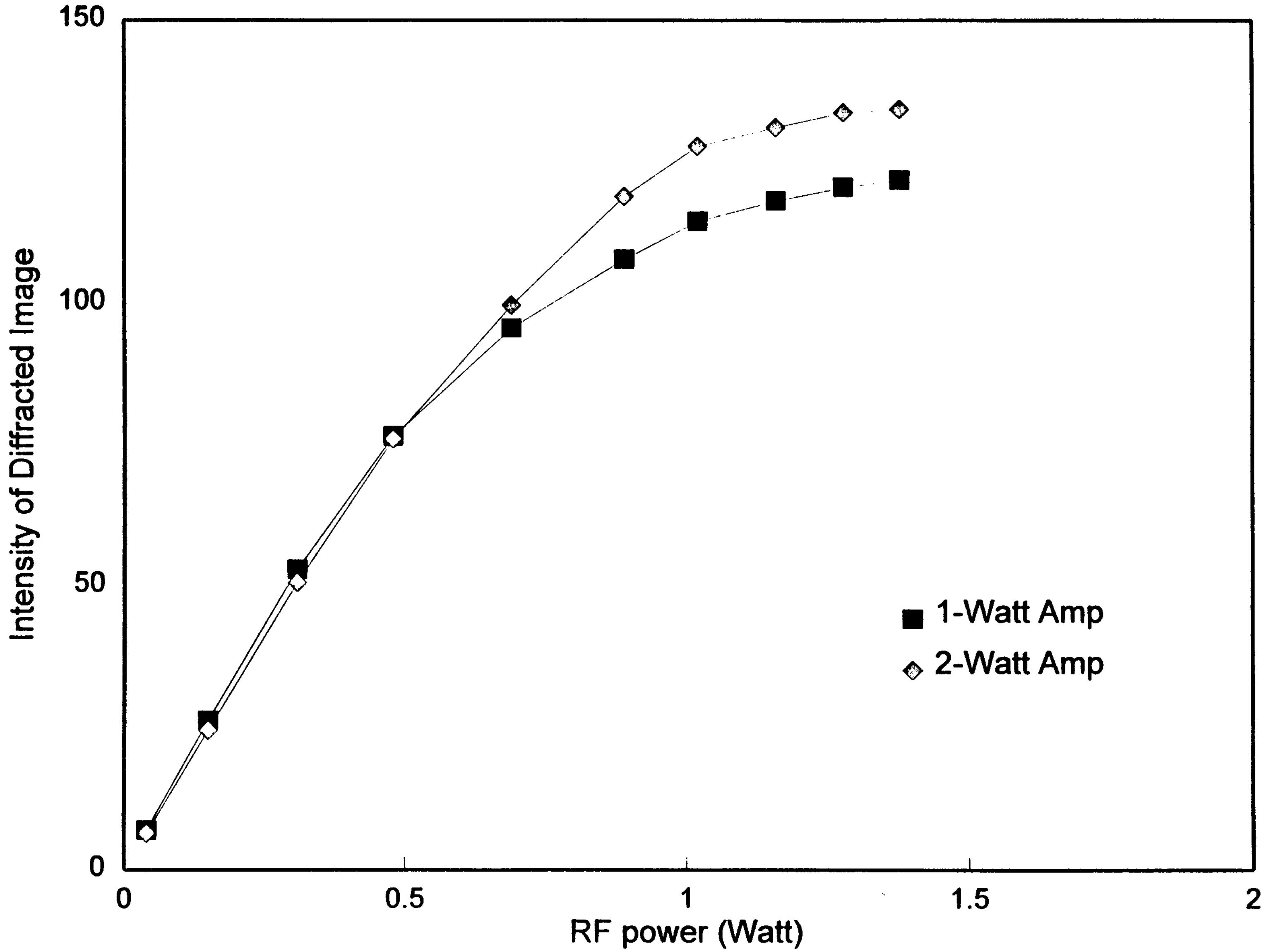
Unfiltered Image

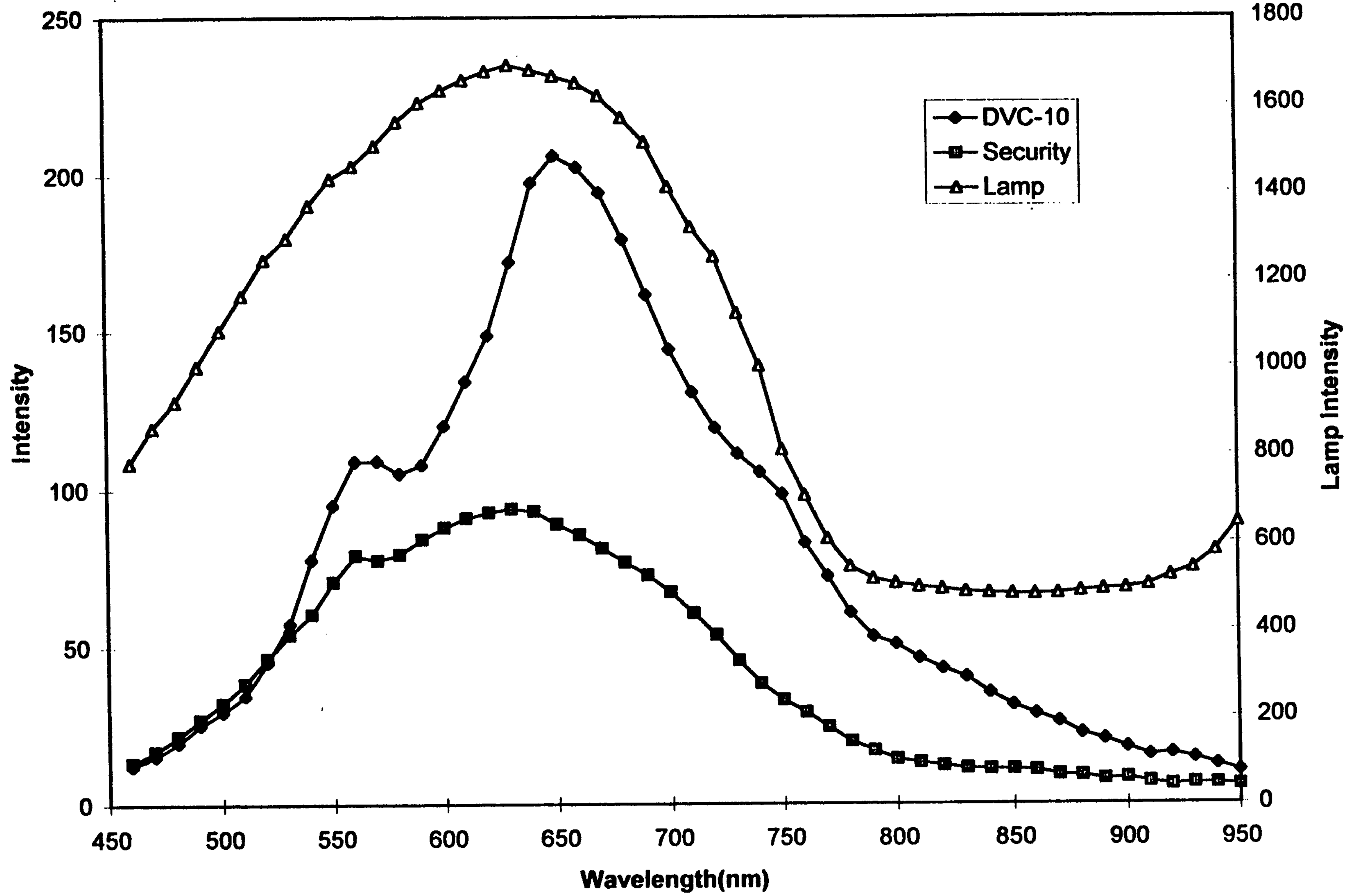


0.19 Watts

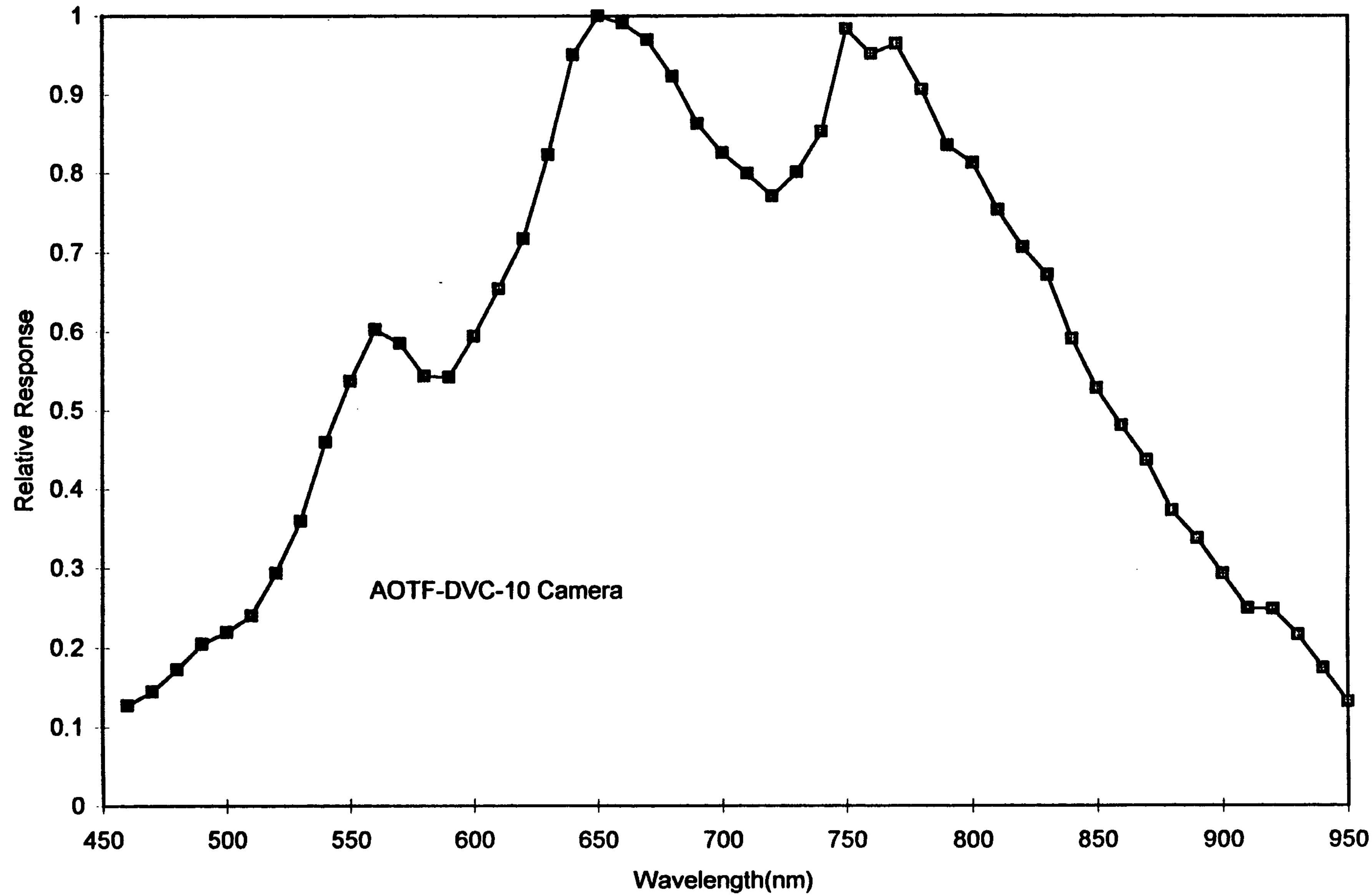


0.65 Watts

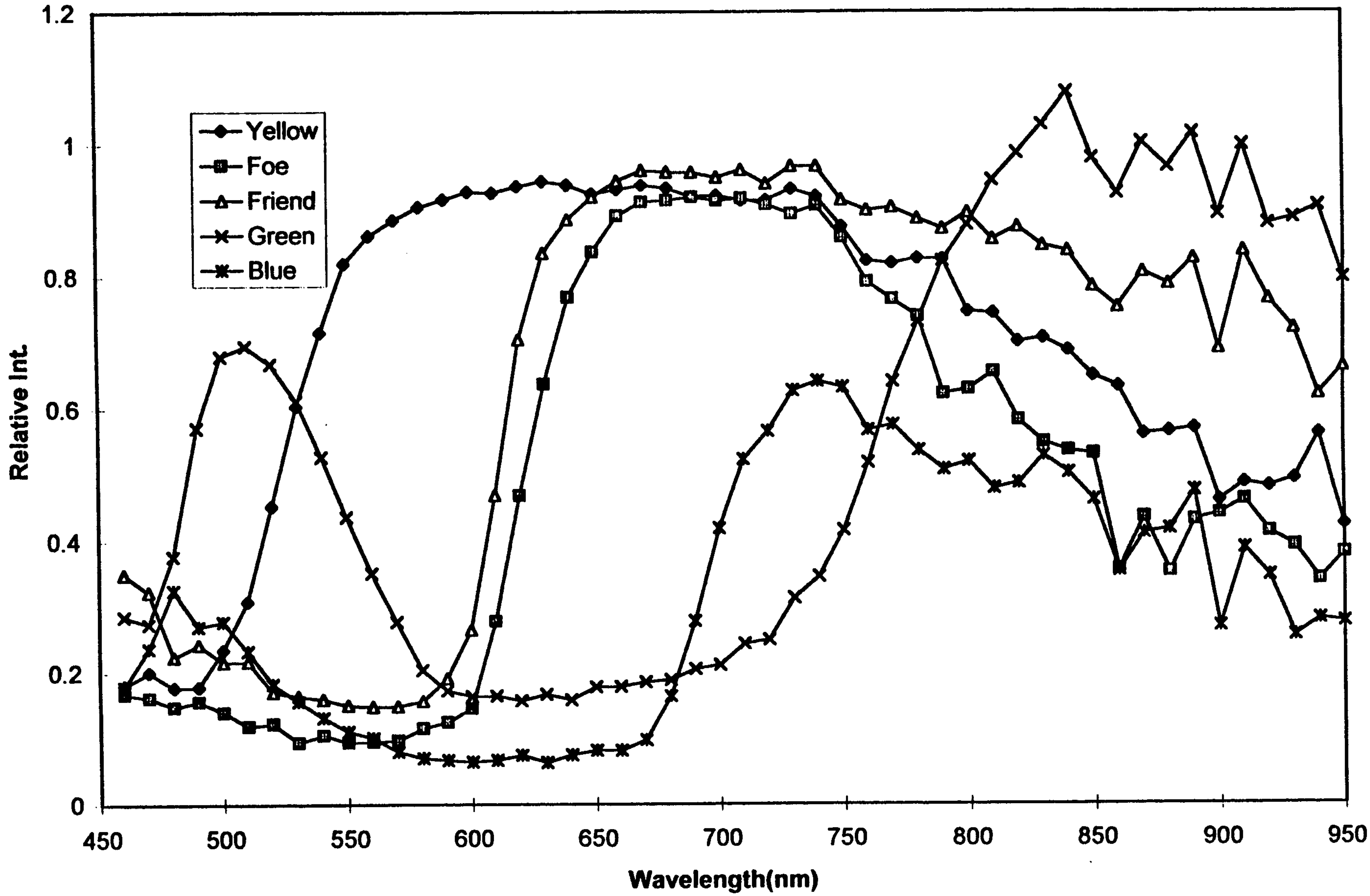

150
100
50
0
Intensity of Diffracted Image
0
0.5
1
1.5
2
RF power (Watt)
1-Watt Amp
2-Watt Amp



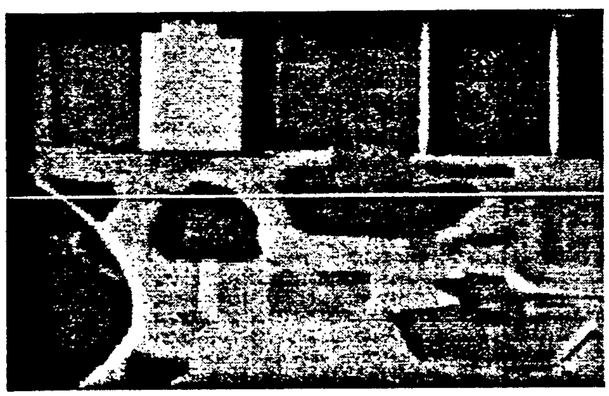
Advanced Materials Corp.



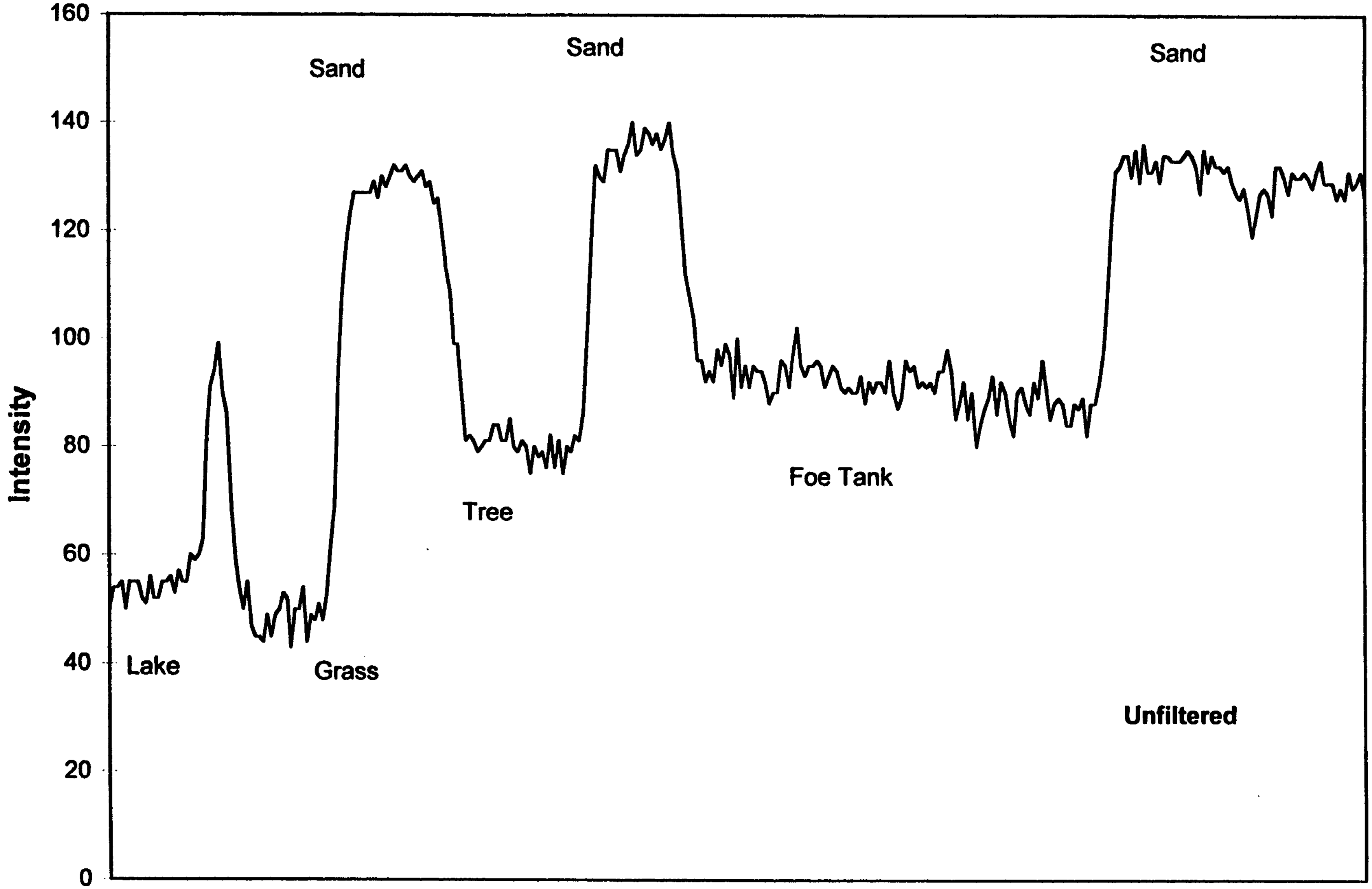
Advanced Materials Corp.

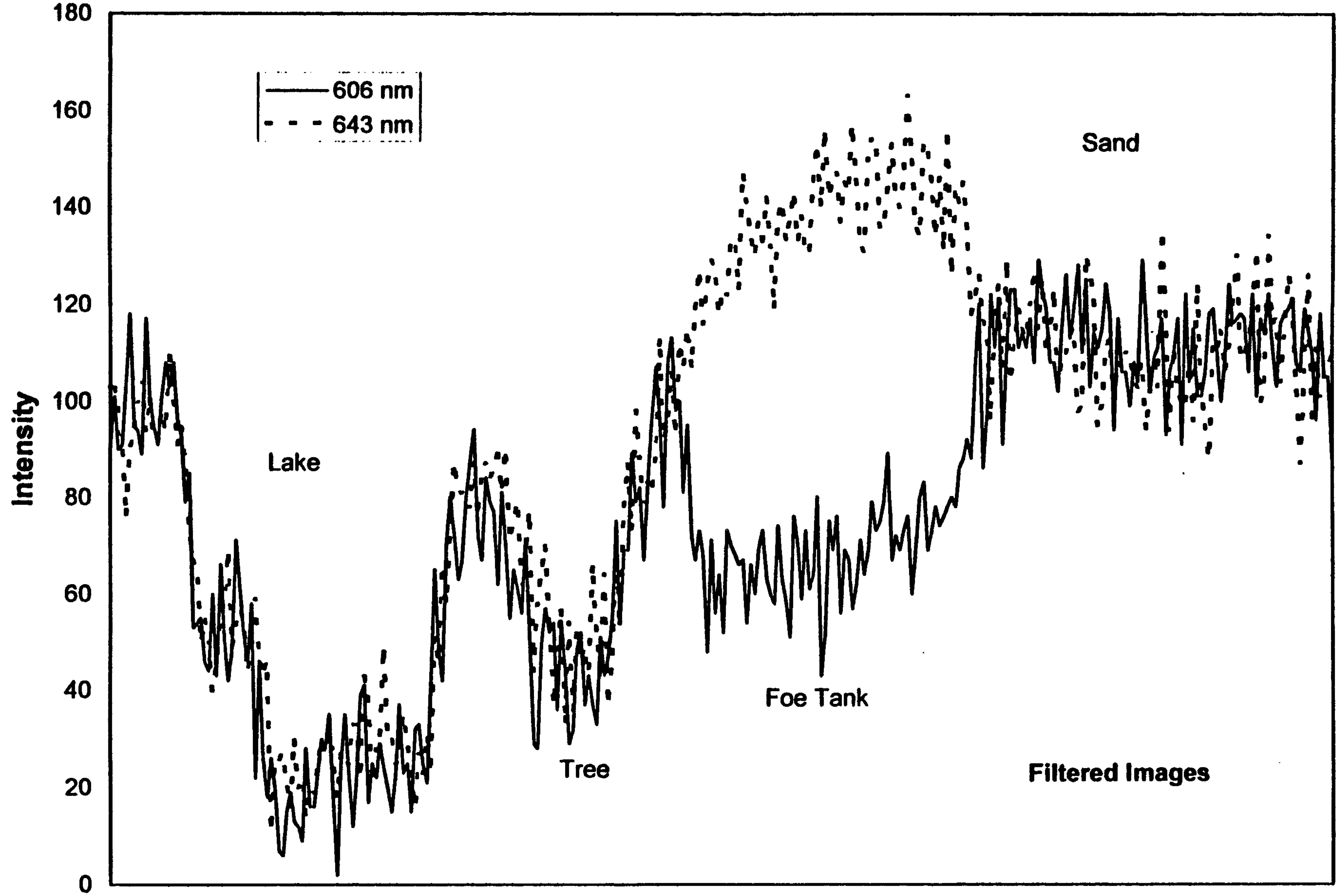


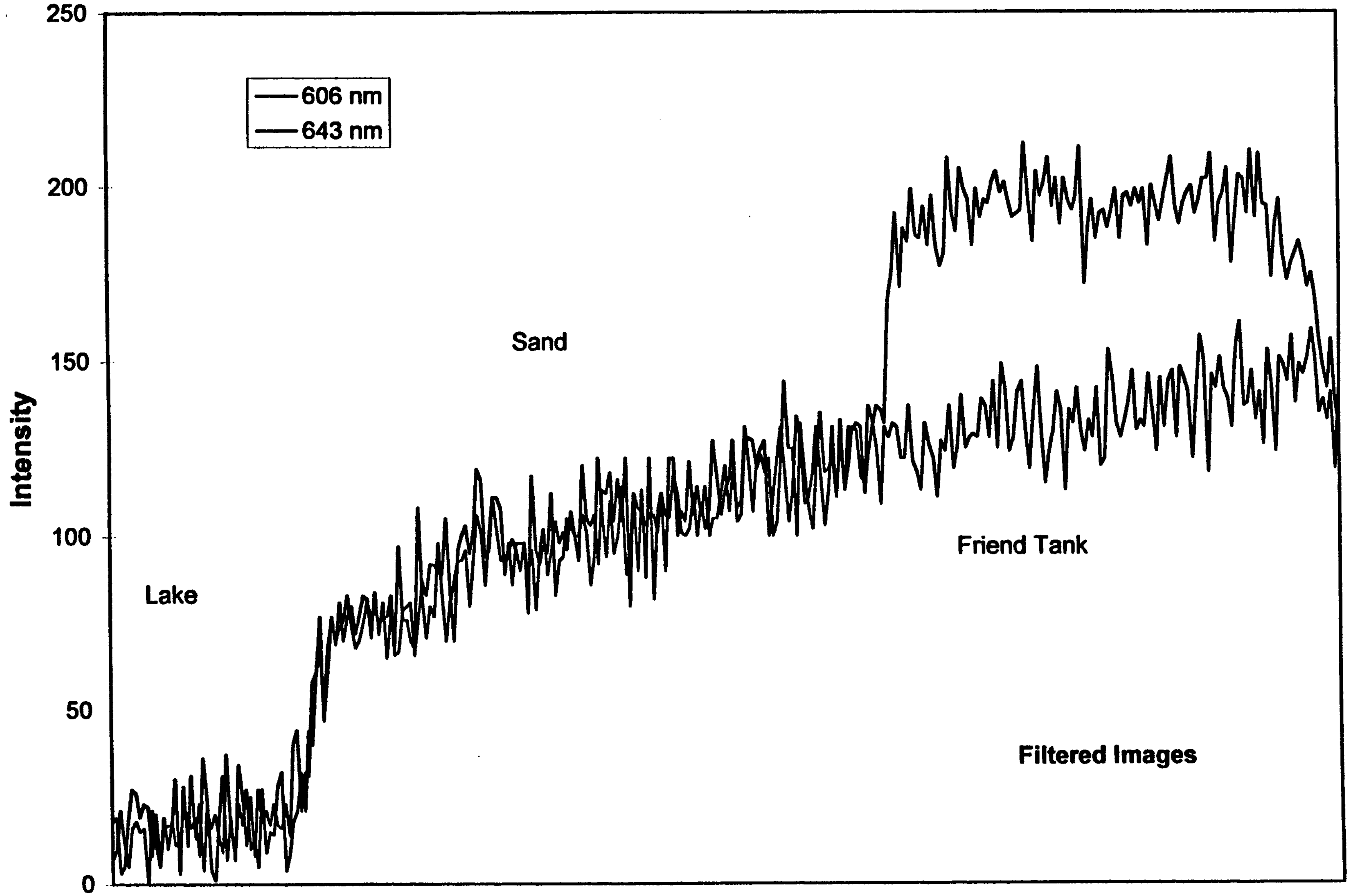
Advanced Materials Corp.



Unfiltered Image


Intensity
160
140
120
100
80
60
40
20
0
Sand
Sand
Sand
Lake
Grass
Tree
Foe Tank
Unfiltered


180
160
140
120
100
80
60
40
20
0
Intensity
606 nm
643 nm
Lake
Tree
Foe Tank
Sand
Filtered Images



Advanced Materials Corp.

(a) Filtered at 643 nm

(b) Filtered at 603 nm

(c) Processed Image

Photonic Systems Incorporated

Simultaneous Multispectral Imaging with 12 Parallel Channel Tunable Camera

J. A. Carter III, D. R. Pape,
Photonic Systems Inc., Melbourne, Florida
URL http://photon-sys.com/

M. L. Shah,
MVM Electronics, Inc., Melbourne Florida

Simultaneous Multispectral Imaging

Introduction

Photonic Systems Incorporated

- Background and Chronology
- Simultaneous Multispectral Imaging System (SMIS) Description
- SMIS Design Methodology
- Compensation Error Residuals for Increasing Design Freedom
- Acoustic Transducer Design
- Prototype Performance
- Conclusion
- Credits

Simultaneous Multispectral Imaging

Background and Chronology

Photonic Systems Incorporated

- July of 1992, PSI and MVM jointly proposed "*A Simultaneous electronically variable Multi-spectral Imaging System*" to NASA JPL as a Phase I SBIR effort that was funded as Contract NAS7-1222.
- August of 1993, the Phase II proposal describing the development of the Simultaneous Multispectral Imaging System (SMIS) was submitted
- April of 1994, NASA JPL funded the contract as NAS7-1311.
- April of 1996, Prototype AOTF and compensation optics set were presented at the SPIE *AeroSense* Technical Exhibit to provide a preliminary demonstration of these technologies.
- PSI and MVM are now completing that system.

Simultaneous Multispectral Imaging

PSI
Photonic Systems Incorporated

Simultaneous Multispectral Imaging System

- Fully compensated AOTF based imager.
- Simultaneous imaging of multiple spectral bands on separate image sensors.
- Extensible design to allow additional band channels as well as broadband imaging.
- Image data for polarimeteric scenes or non-polarimatric scenes with double the number of bands.
- Astronomical imaging for NASA prototype system.
  - 2 polarization channels
  - 6 image band channels
  - 2 AOTF nodes
  - 3 image channels separated by dichroic filters
  - 512 x 512 image pixels per channels
  - high precision, long integration, cooled CCD sensors

Simultaneous Multispectral Imaging

Photonic Systems Incorporated

Simultaneous Multispectral Imaging System

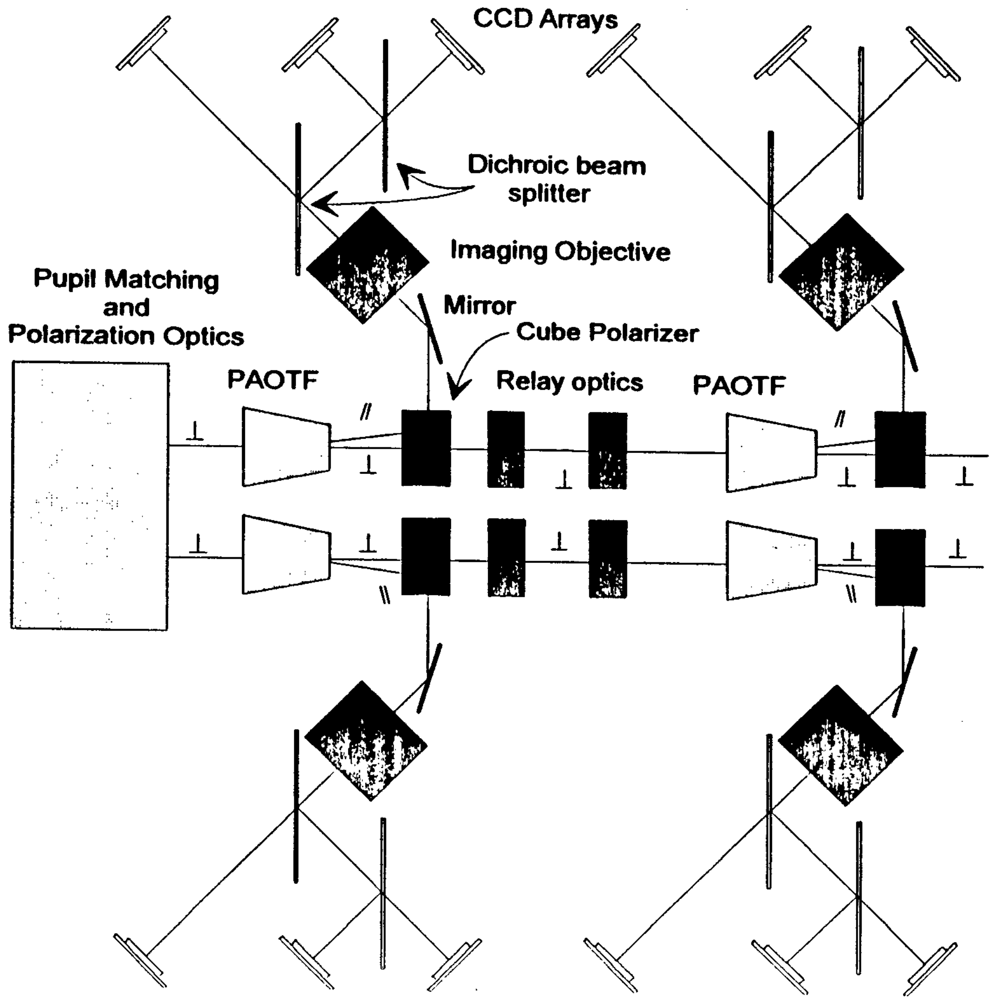
Wavelength Range	420 nm to 700 nm	6 or 12 selections, continuous range
Spectral Resolution	3 nm, 9 nm, or 15 nm	Programmable, user defined *
Spatial Resolution	500 resolvable elements	Rayleigh criteria *
Throughput Efficiency	greater than 80%	peak at center wavelength for each of two polarized fields

* *spectrally dependent*

Simultaneous Multispectral Imaging

System Schematic

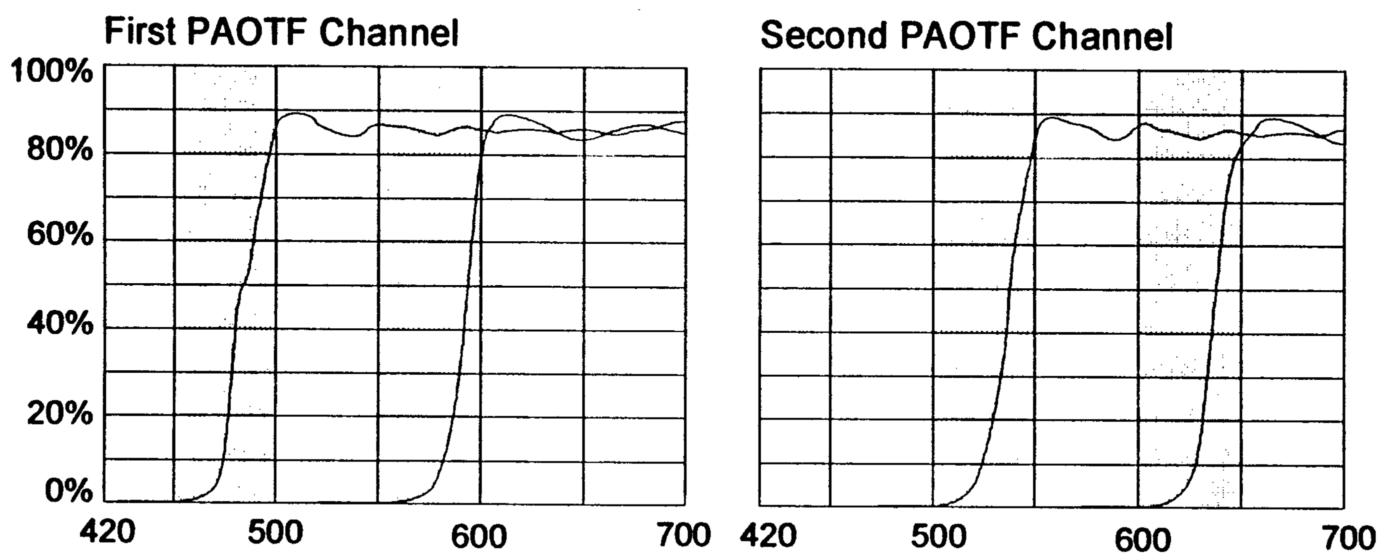
Photonic Systems Incorporated



Simultaneous Multispectral Imaging

PSI
Photonic Systems Incorporated

Spectral Passband Map



indicates transition (dead) band

Simultaneous Multispectral Imaging

Design Methodology

Photonic Systems Incorporated

- FORTRAN software to model an arbitrary AOTF within CodeV from Optical Research Associates
  - User Define Surface interface for CodeV
  - Pseudo-normal allows CodeV to "refract" ray into proper direction
  - Only runs on VAX (DEC) or Sparc (Sun) platforms
  - Too slow for system optimization
- Stand-alone, custom software written in C to optimize an arbitrary AOTF using dispersive compensation optics
  - Physical optics ray tracing in AOTF crystal
  - Traces rays through a variety of compensation optics types
  - Damped Least Squares optimization of compensation optics
- Candidate compensation designs returned to CodeV for critical system performance assessment

Simultaneous Multispectral Imaging

Residual errors for increasing degrees of design freedom

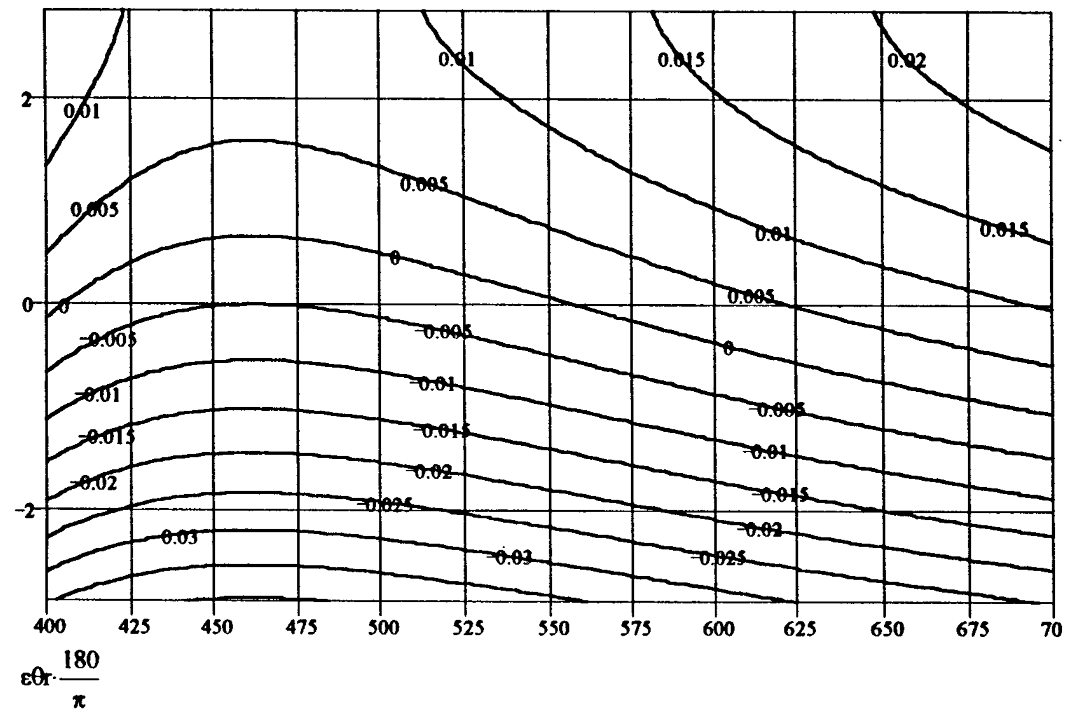
Photonic Systems Incorporated

- Wedged AOTF to compensate dispersive aberrations
- Compensation residuals for 2 degrees of freedom
- Compensation residuals for 3 degrees of freedom

Simultaneous Multispectral Imaging

Wedged AOTF compensation residuals

Photonic Systems Incorporated

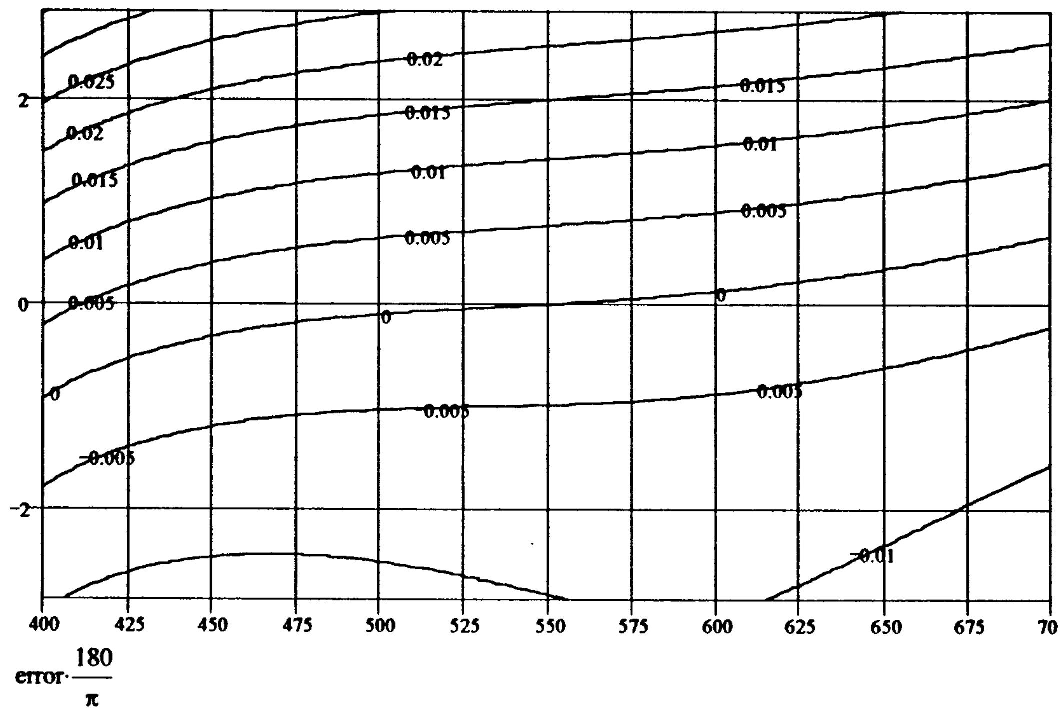


± 3.0° FOV, 512 pixels
0.0117° per pixel

Simultaneous Multispectral Imaging

Compensation residuals for 2 degrees of freedom

Photonic Systems Incorporated

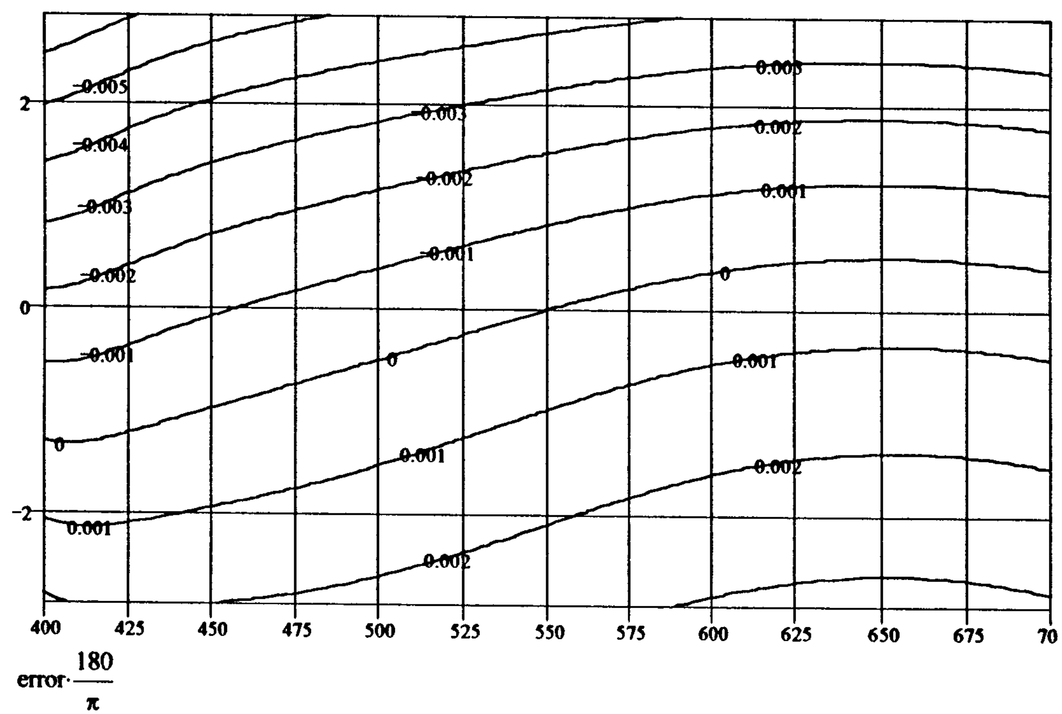


± 3.0° FOV, 512 pixels
0.0117° per pixel

Simultaneous Multispectral Imaging

Compensation residuals for 3 degrees of freedom

Photonic Systems Incorporated

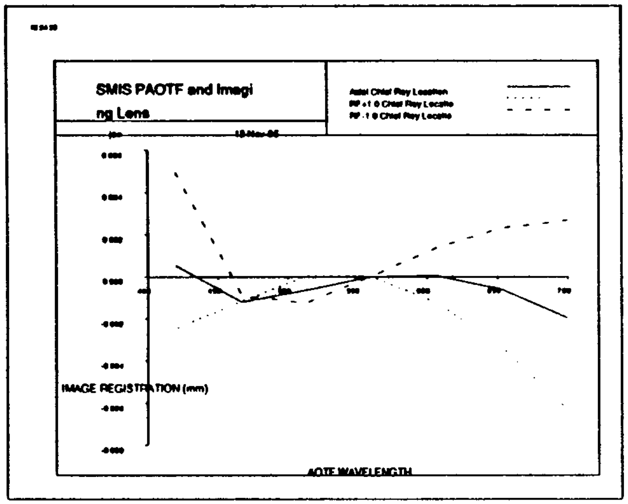


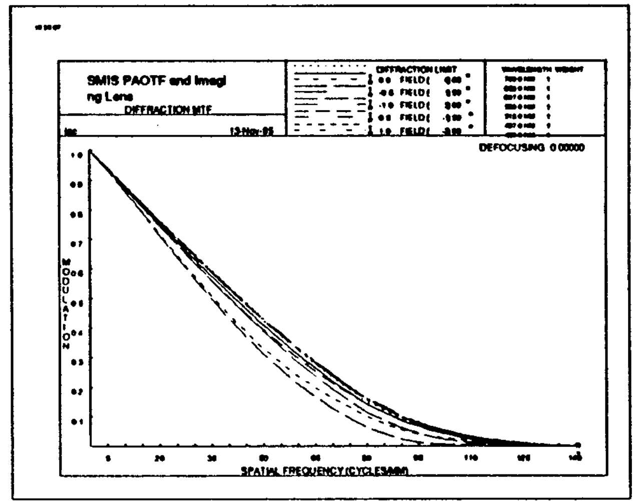
± 3.0° FOV, 512 pixels
0.0117° per pixel

Simultaneous Multispectral Imaging

Photonic Systems Incorporated

SMIS optical design performance for AOTF, compensation and custom image objective





- Pixel subtends 19 by 19 microns for the SMIS system.
- The registration for the center of the image is well within 4 microns
- The edges of the image register within no more than 9 microns.

Simultaneous Multispectral Imaging

Acoustic Transducer Design

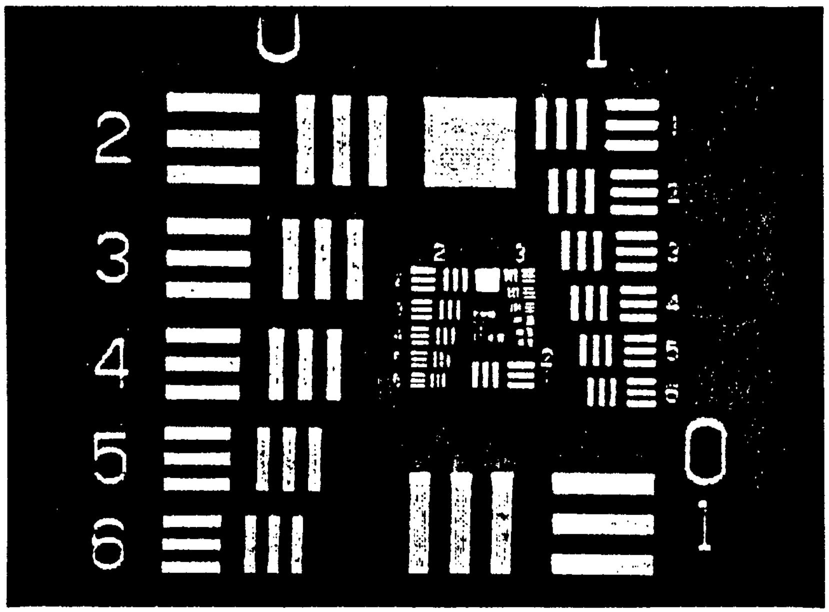
Photonic Systems Incorporated

- Acoustic beam side-lobes give spatially shifted "ghost" images
- Transducer design issues:
  - Absolute minimum energy in acoustic beam sidelobes - transducer shape and apodization
  - Segmented transducer scheme to adjust raw transducer impedance for RF matching.
- Manhar Shar of MVM Electronics developed novel transducer scheme that addresses these issues and provides excellent performance for the SMIS and future image sensor developments.
  (Patent forthcoming)

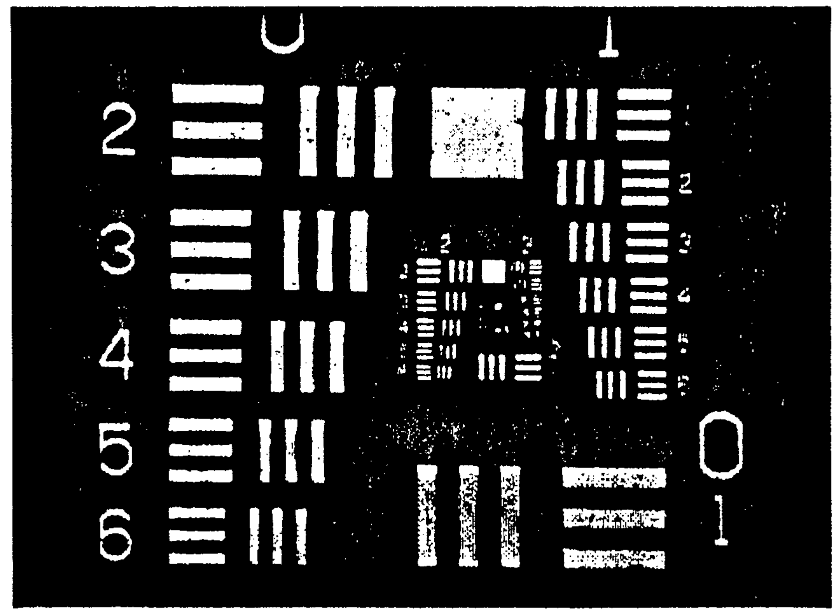
Simultaneous Multispectral Imaging

Acoustic Transducer Performance

Photonic Systems Incorporated



Early AOTF Prototype



Final AOTF Design

Simultaneous Multispectral Imaging

Prototype Performance

Photonic Systems Incorporated

- SMIS is currently in the fabrication and integration process.
- Preliminary results are limited to the lab bench breadboard optical system.
- Video tape very quickly made; please accept my apologies.

Simultaneous Multispectral Imaging

Conclusion

Photonic Systems Incorporated

- **PSI and MVM Electronics have developed a completely compensated tunable camera system**
  - provides for simultaneous multispectral imaging
  - gives polarimetric data when appropriate
  - allow system to be extended with additional channels
  - provides a broad band image port
- **Compensation provides fraction of a pixel image registration for all points in the image over the entire spectral band.**
- **Compensation optics are designed externally to the AOTF**
  - represent a reduced cost compared to high precision wedges in the AOTF crystal fabrication.
  - provides adjustment for AOTF fabrication variance at the time of system integration and thus improves the yield of acceptable AOTF devices

Simultaneous Multispectral Imaging

Credits

Photonic Systems Incorporated

PSI and MVM would like to thank Dr. Robert Nelson, of the NASA Jet Propulsion Laboratories, for his encouragement, guidance, and support. Without the funding from the NASA Small Business Innovative Research grant sponsored by Dr. Nelson, this important technology would not be available to the research and commercial communities.

JPL

Polarimetric Hyperspectral Imaging Systems and Applications

Li-Jen Cheng, Colin Mahoney, George Reyes, and Clayton La Baw
Center for Space Microelectronics Technology
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

and

G.P. Li
Department of Electrical and Computer Engineering
University of California
Irvine, CA 92717

* Sponsored by NASA, ASTRO, MCSC, and SSDC

JPL

AOTF IS:

A REAL-TIME PROGRAMMABLE,
HIGH-RESOLUTION SPECTRAL BANDPASS FILTER
WITH POLARIZATION BEAM SPLITTING CAPABILITY

incorporated with focal plane detector array(s), optics,
& electronic subsystems

↓

Polarimetric Hyperspectral Imaging Instrument

↓

Image Data Set
As Function Of Wavelength And Polarization
with spectral resolution adequate for material characterization

JPL

Advantages of AOTF-PHI System

Real-time collection of image data

Spectral
Polarization
Time variation.

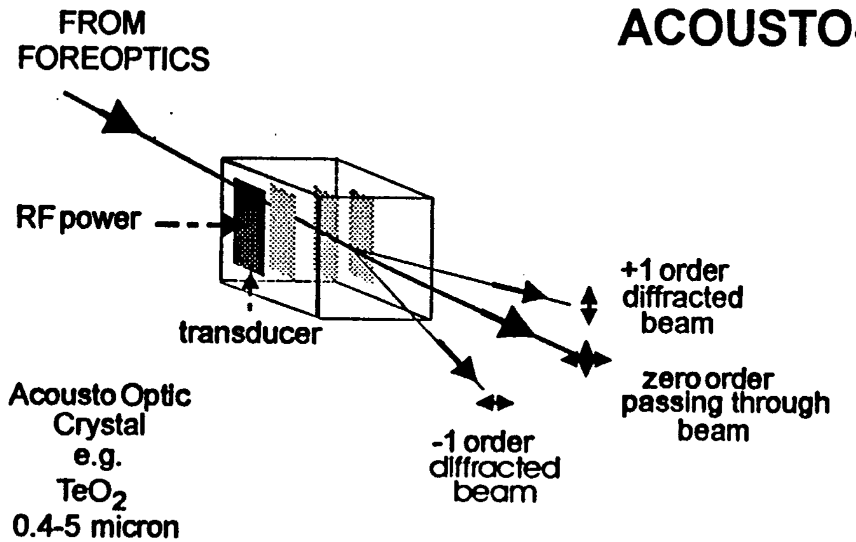
Operational flexibility, fast programmable

Take only needed data at desired wavelengthes.

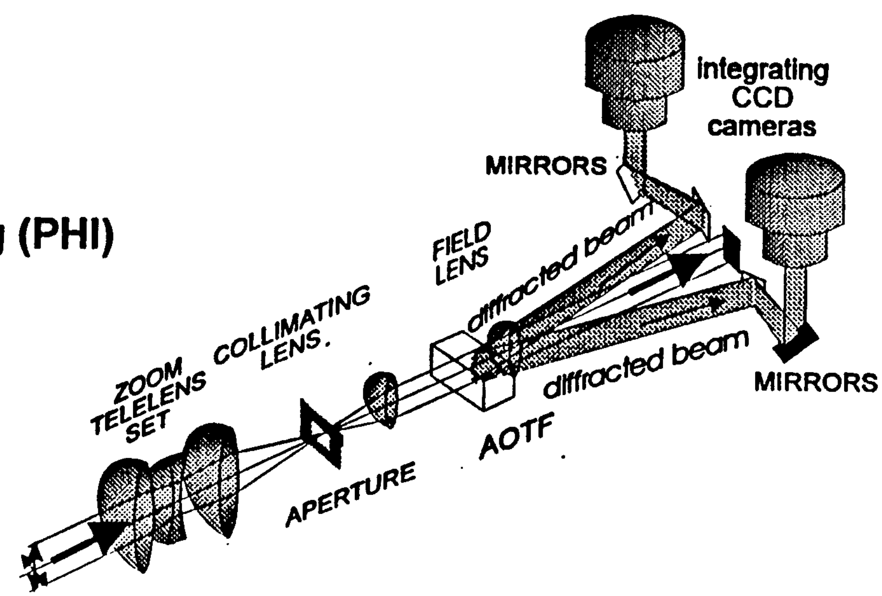
Compact, light-weight, reliable, and low cost

Use on space and airborne platforms, ground vehicles, and hand-held.

ACOUSTO-OPTIC TUNABLE FILTER (AOTF)

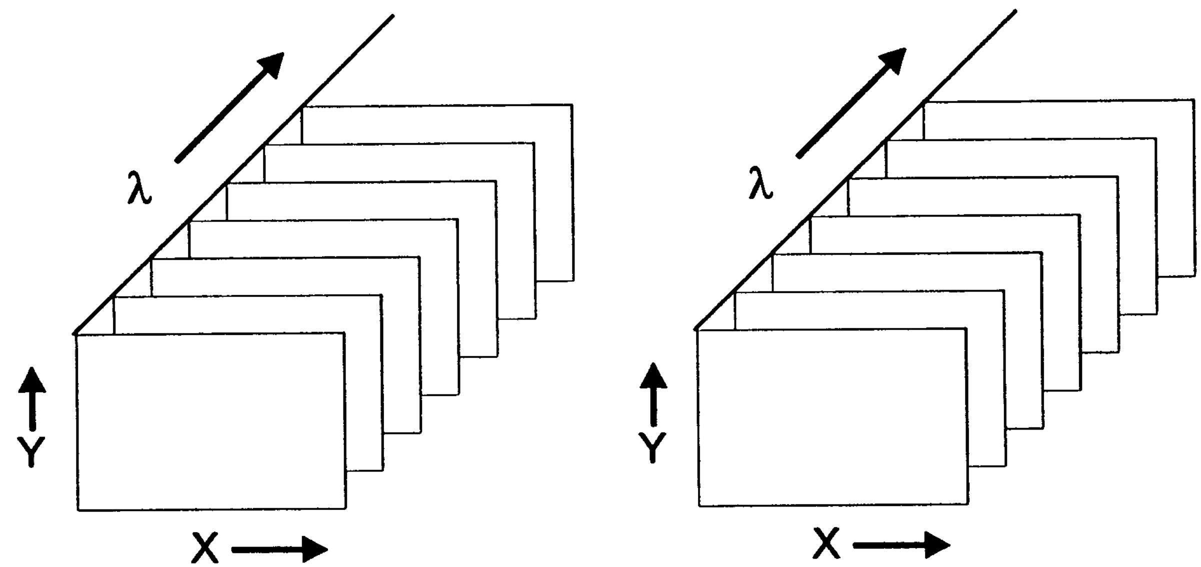


AOTF
Polarimetric
Hyperspectral Imaging (PHI)
System



JPL

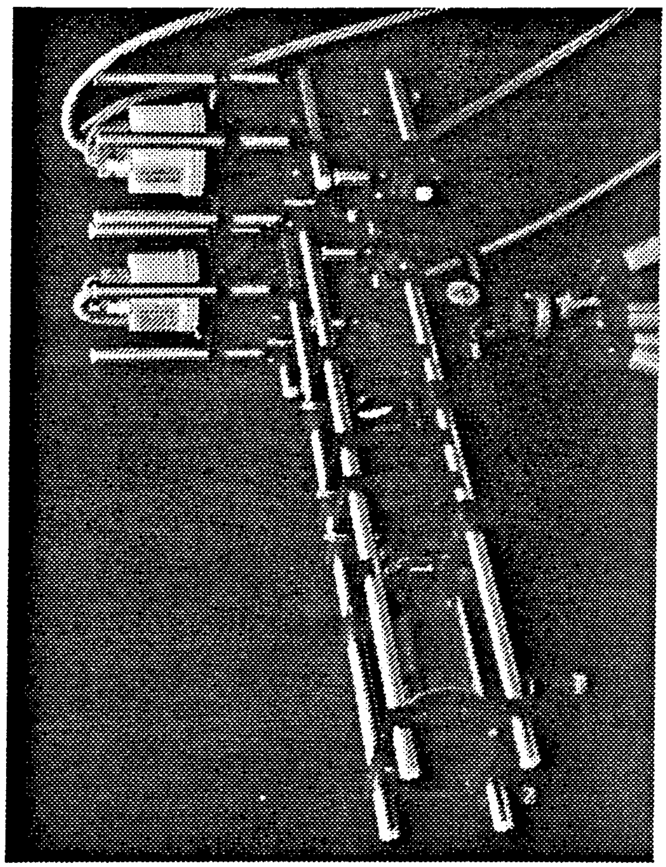
AOTF PHI IMAGE CUBES

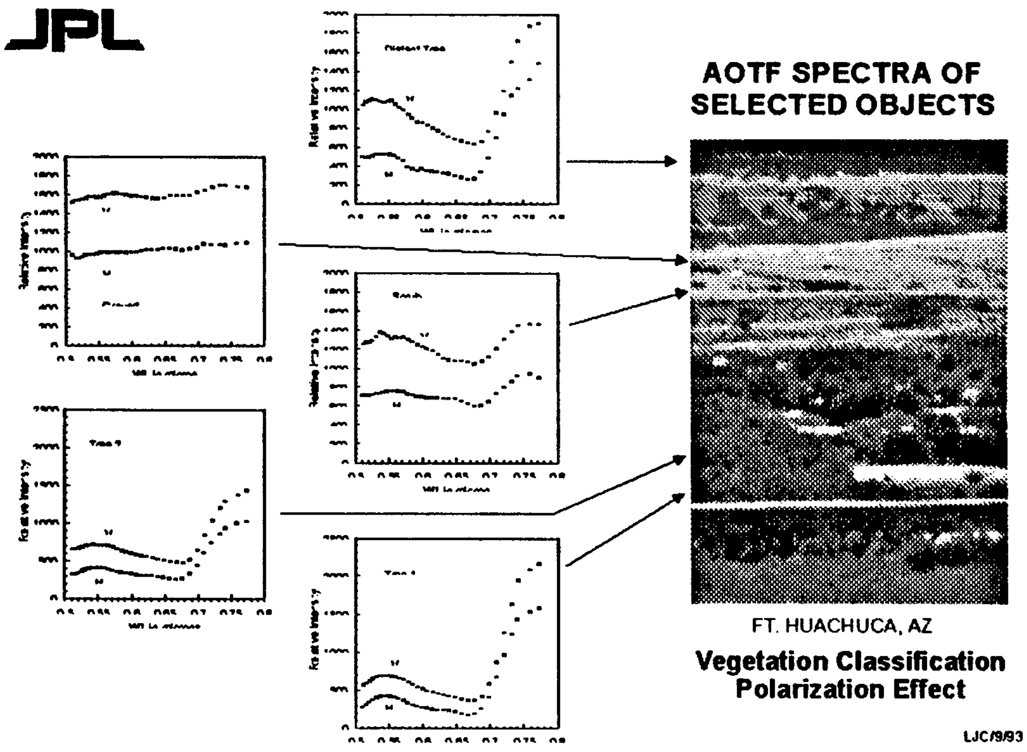


with polarization electric vectors orthogonal to each other

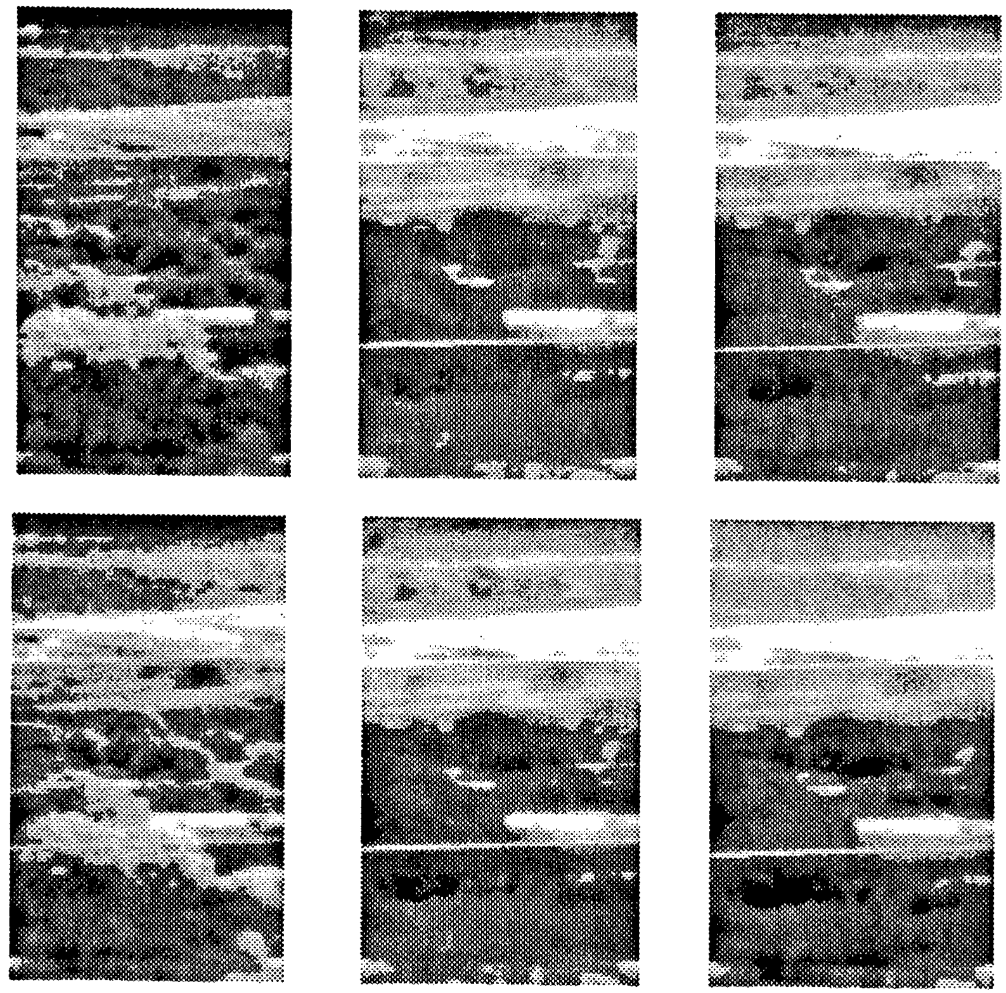
Signal at each pixel in the cube is light intensity
that can be converted into other physical parameters
such as:

spectral derivative images
palorization difference images



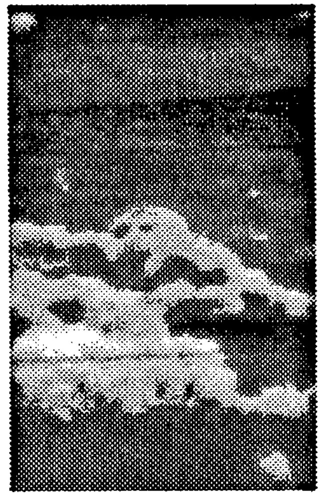

AOTF SPECTRA OF
SELECTED OBJECTS
FT. HUACHUCA, AZ
Vegetation Classification
Polarization Effect
LJC/9/93

AOTF SPECTRAL IMAGES

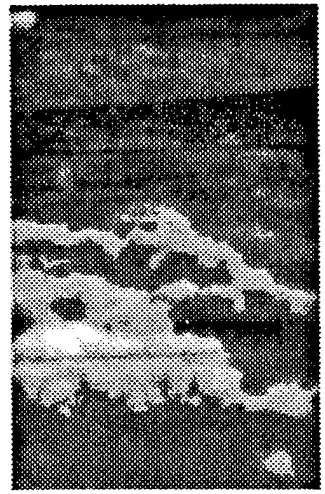


JPL

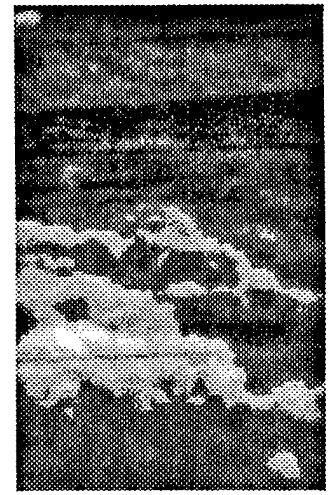
SPECTRAL DERIVATIVE IMAGES AT CHLOROPHYLL RED EDGE



0.742



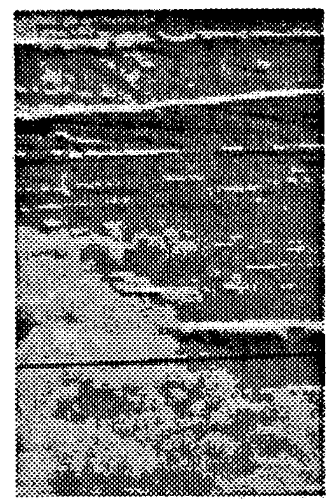
0.734



0.722 µm

0.710

0.699

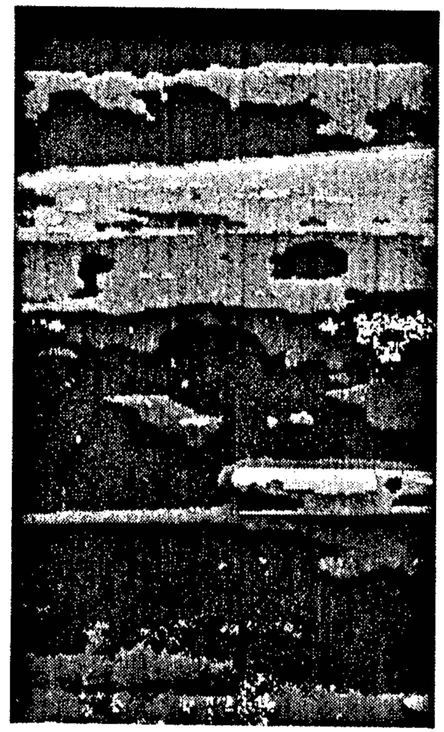


0.688 µm

LJC/10/93

JPL

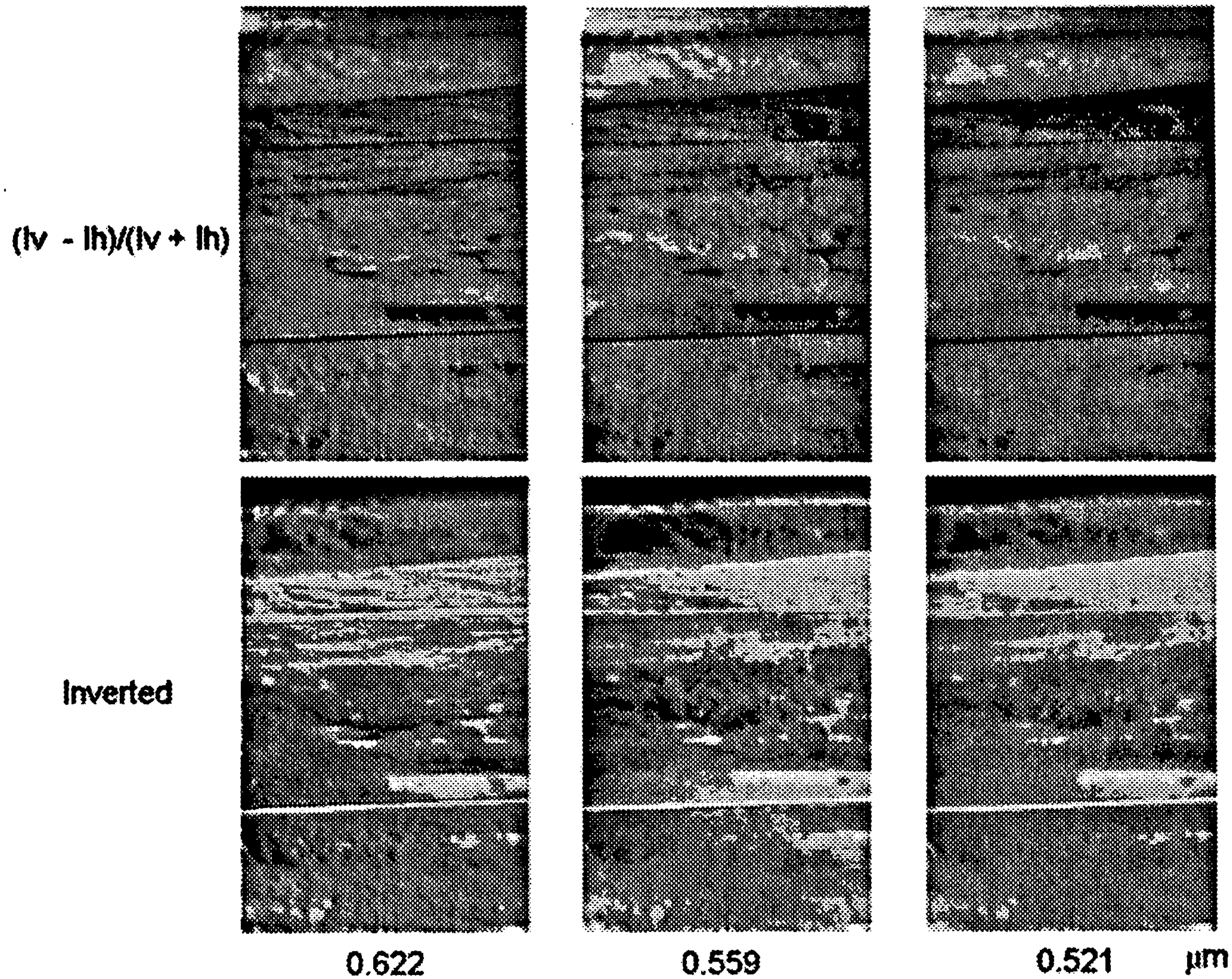
A DETECTION CONCEPT ILLUSTRATION



Via Detecting Mask
Generated
with Expected Characteristics

LJC/6/93

POLARIZATIIION IMAGES



LJC/10/93

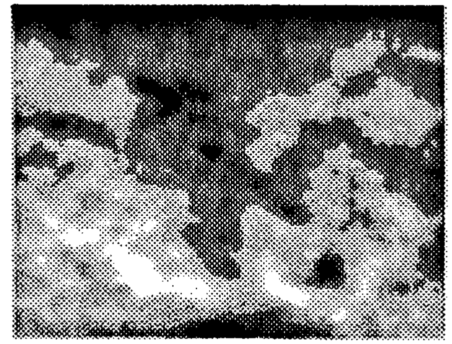
JPL

A Camouflaged Target

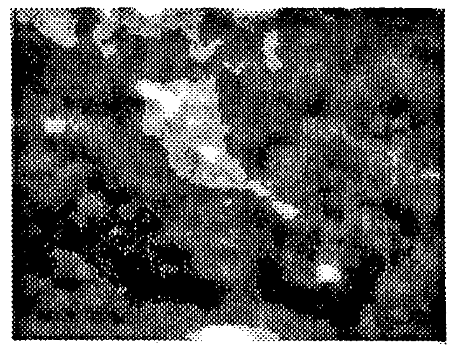
Ft. Huachuca, AZ 4/93

color image
taken by a
35mm camera

differential
polarization image
at 0.56 micron
$P = (I_v - I_h)/(I_v + I_h)$



original



inverted

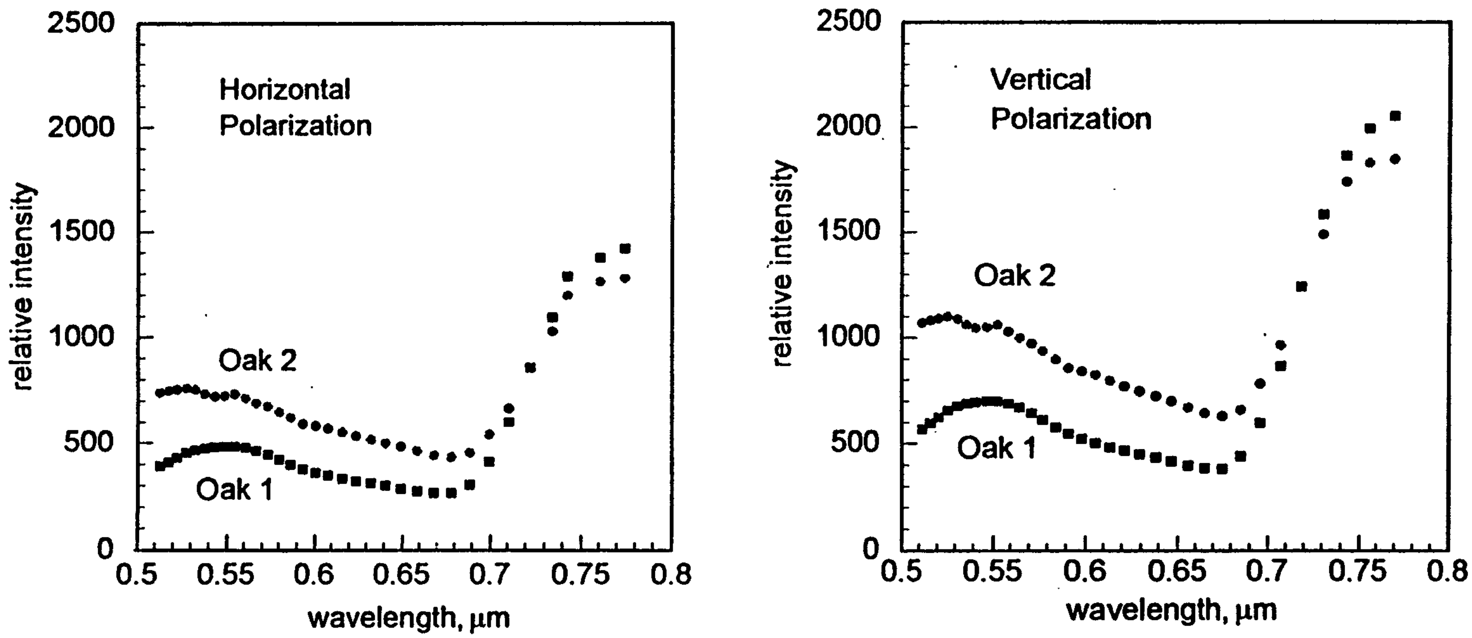
Enlarged images of
camouflaged target

LJC/10/93

AEROSOL SCATTERING
IN ATMOSPHERE

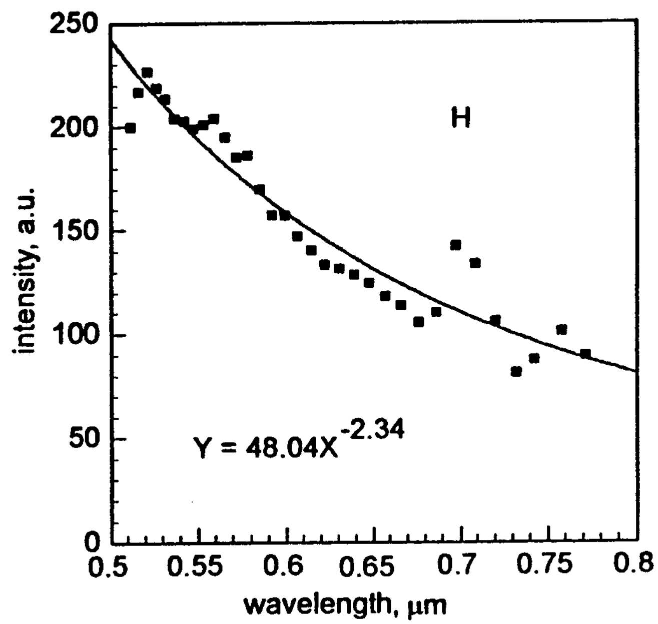
JPL

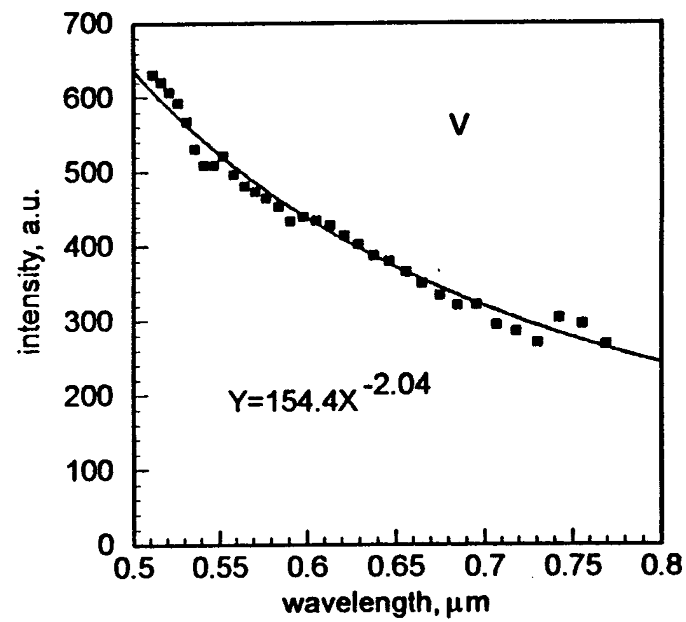
Reflectance Spectra of Two Oaks at Different Distances



JPL

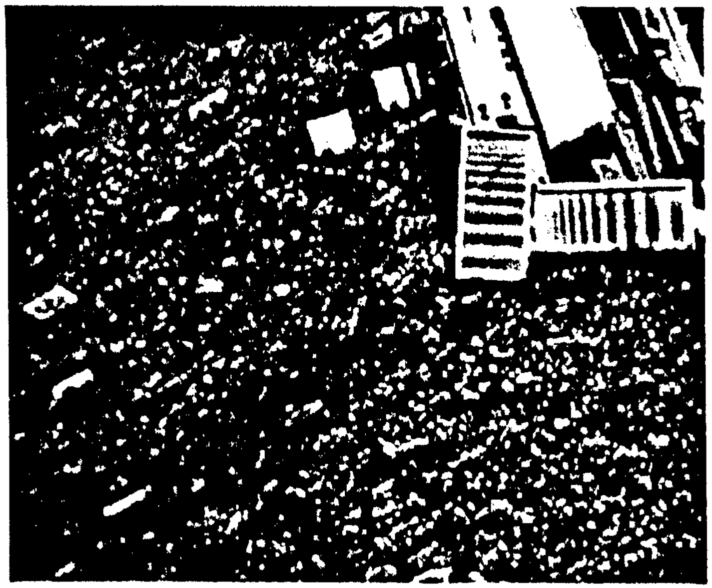
Wavelength Dependence of Scattered Light Due to Aerosol in the Atmosphere



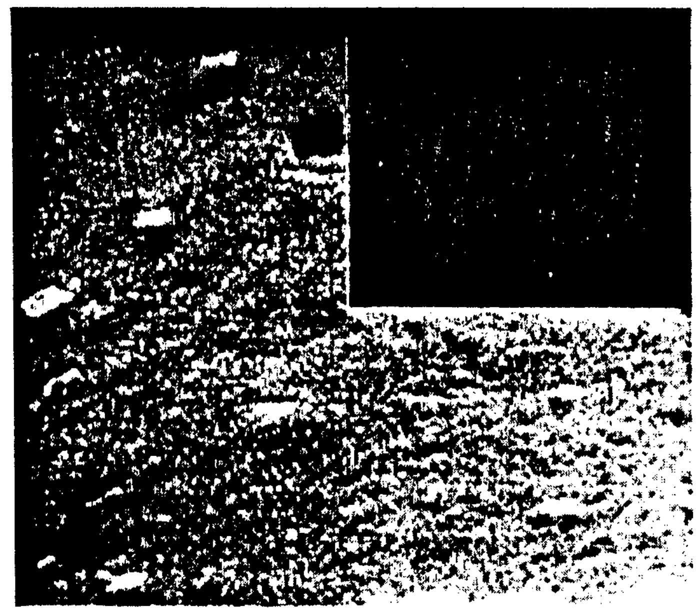


JPL

TARGET DETECTION AND CLUTTER REMOVAL



35 MM COLOR IMAGE
USING AN ORDINARY CAMERA



DIFFERENTIAL POLARIZATION IMAGE
AT 0.52 MICRONS

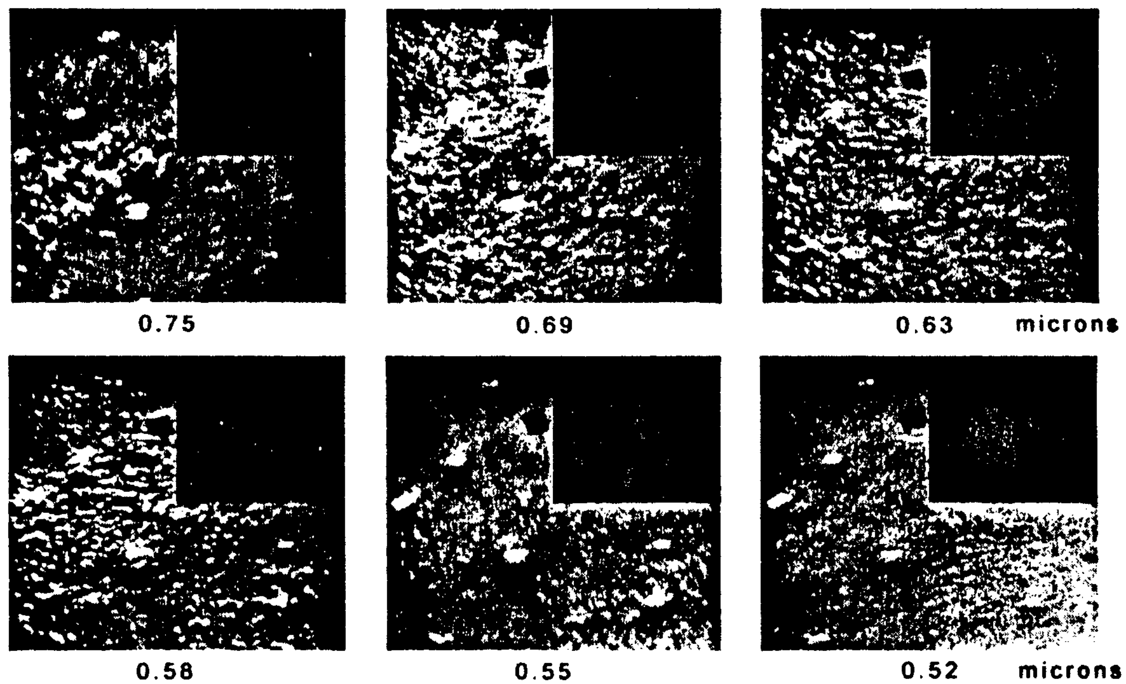
MINES IN ICEPLANT FIELD

LJC/4/94

minepol3.tif

JPL

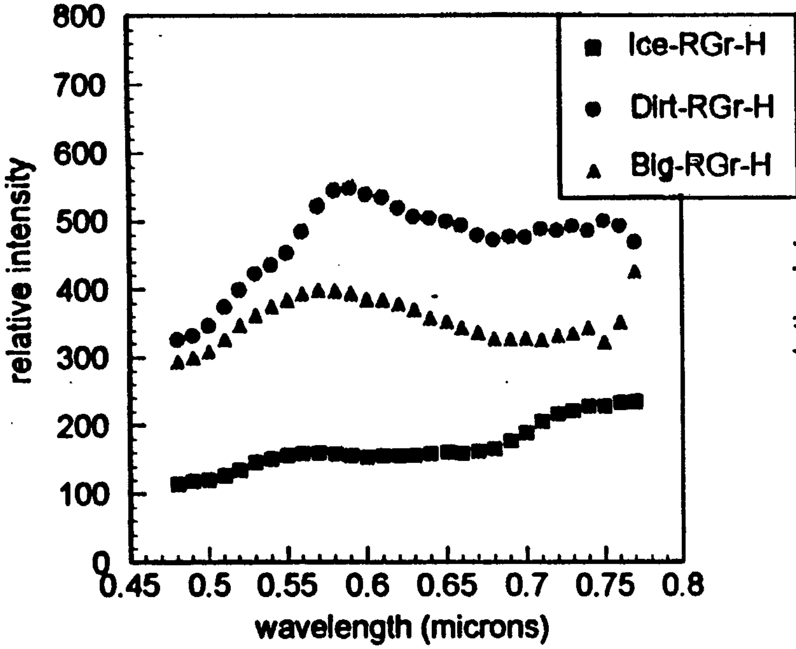
MINES IN ICEPLANT FIELD
POLARIZATION SPECTRAL IMAGES

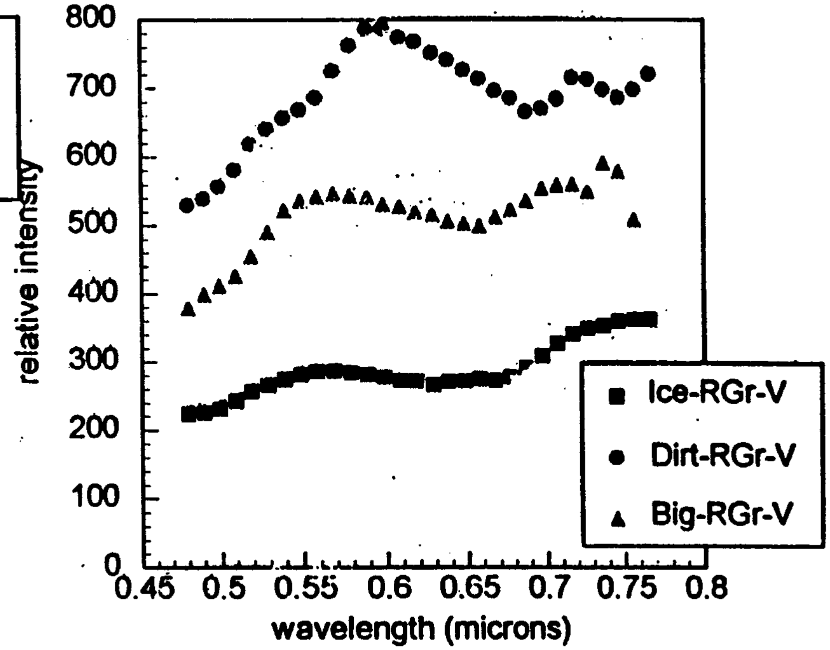


JPL

SPECTRAL MIXING

due to scattered light from neighboring objects





Ice: iceplant field (~400 m)
Dirt: bare ground with a white trailer nearby (~400 m)
Big: close distance (~40 m)

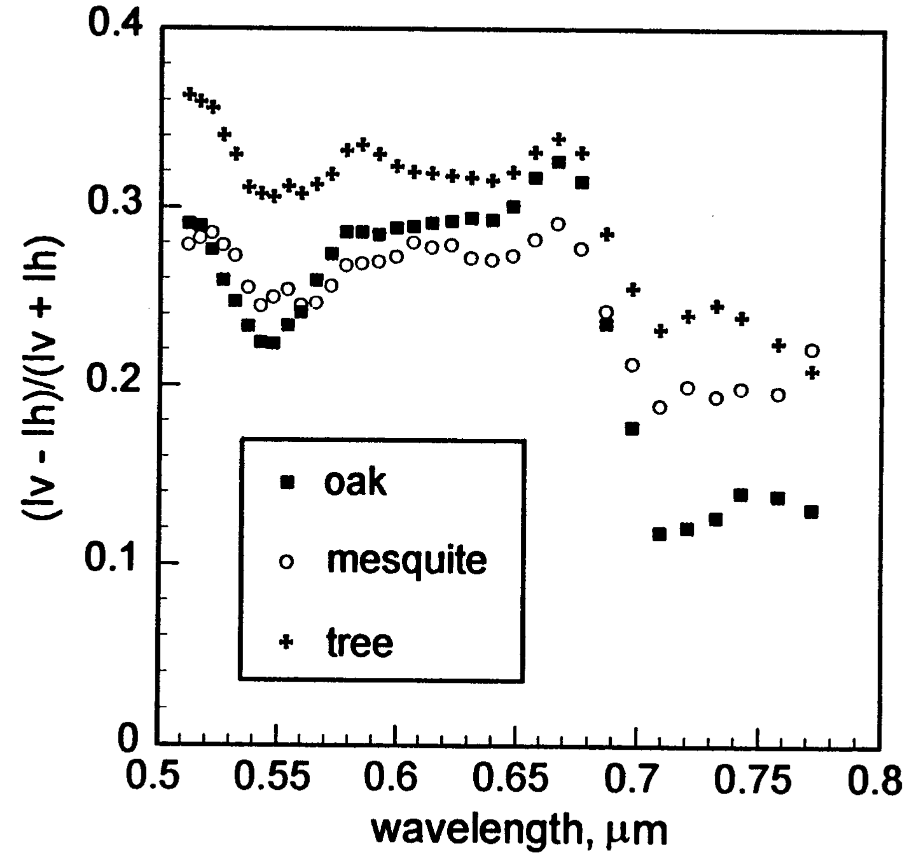
dark green round metallic mine

VEGETATION

AND

POLARIZATION EFFECTS

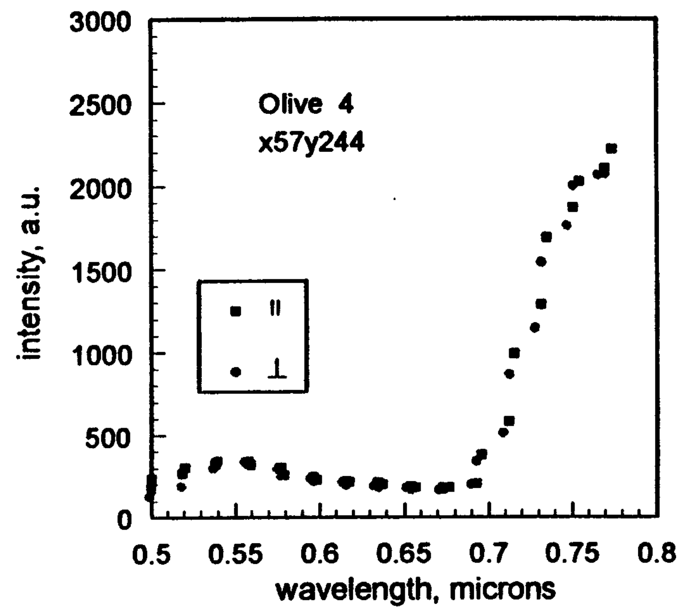
Measured Polarization Spectra of Three Different Trees

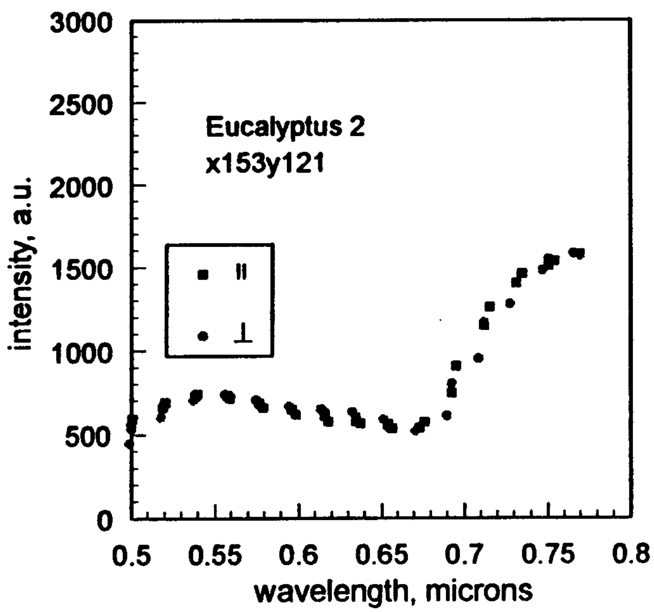


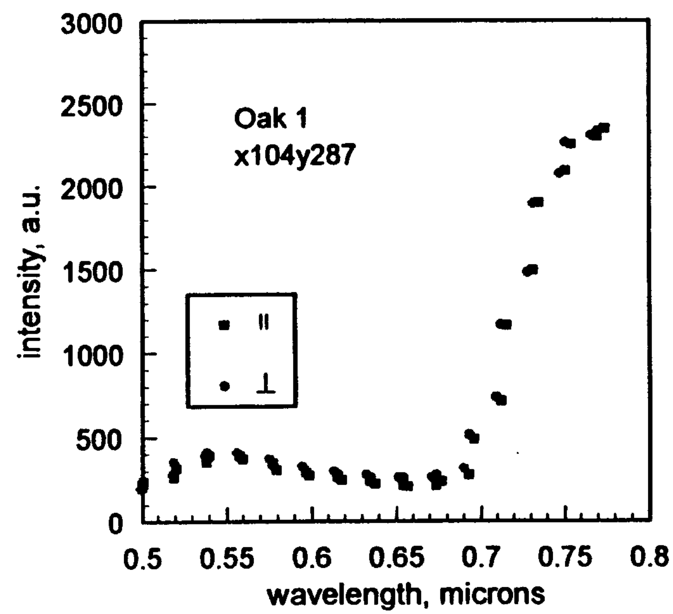
JPL

GREEN LEAF SPECTRA

phase angle = 20

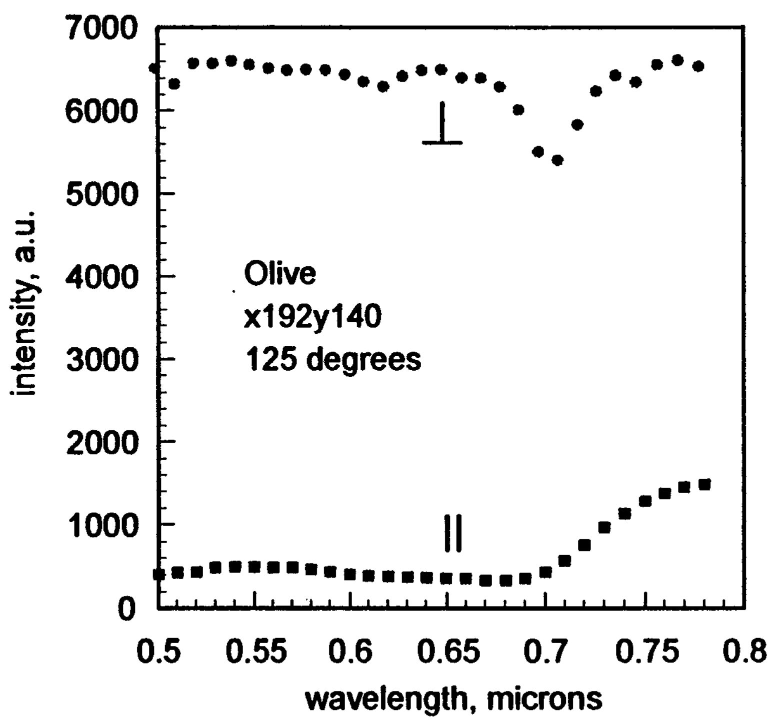


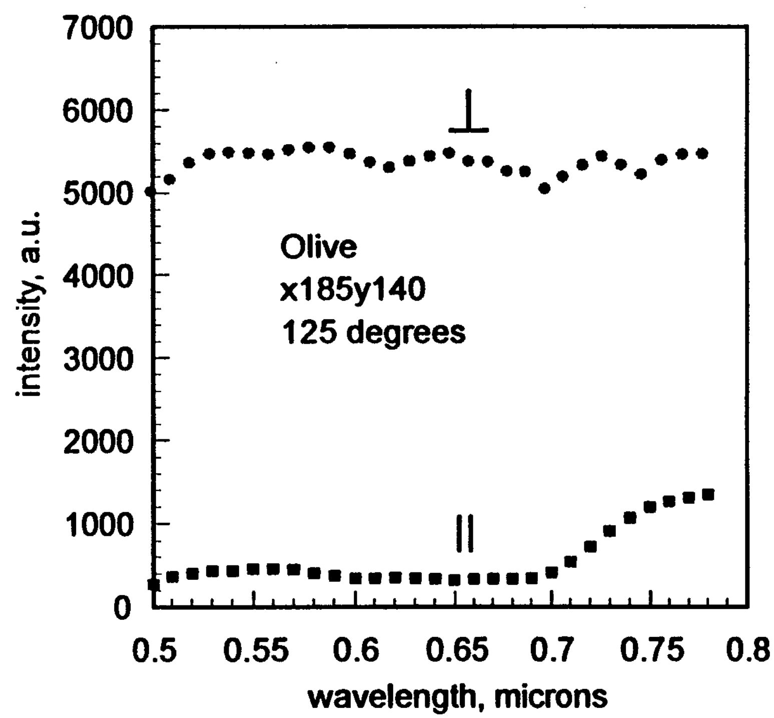




JPL

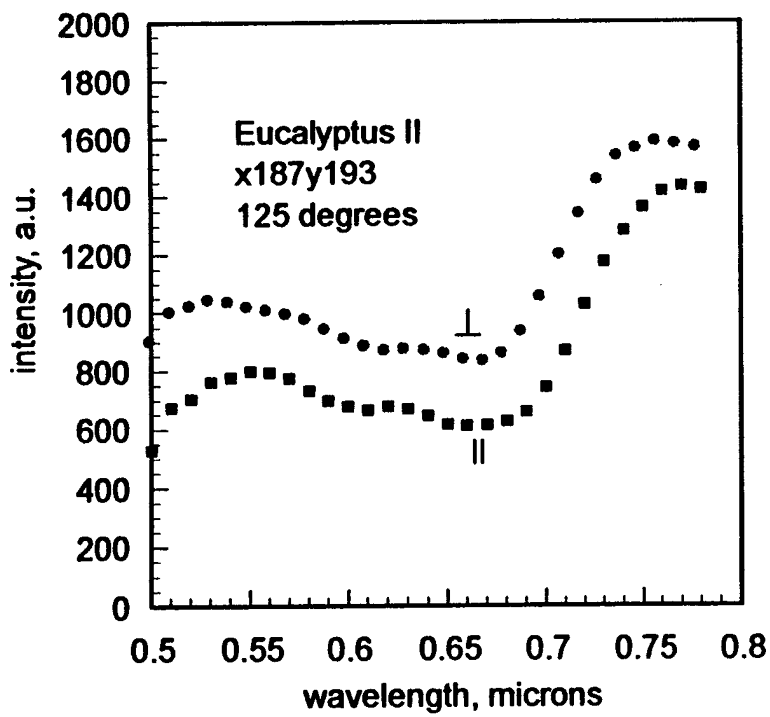
REFLECTIVE SPECTRA OF OLIVE LEAF AT SPECULAR ANGLE

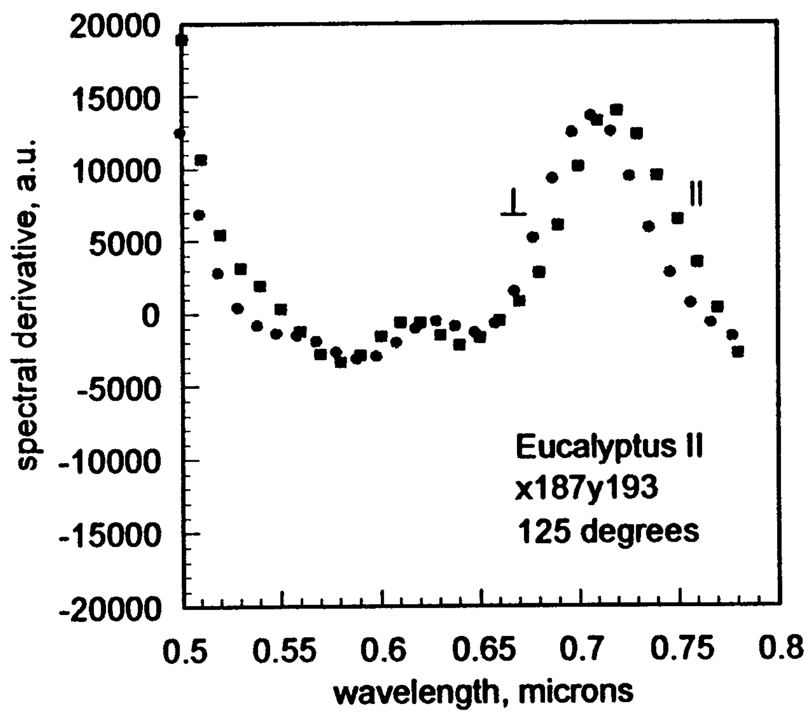




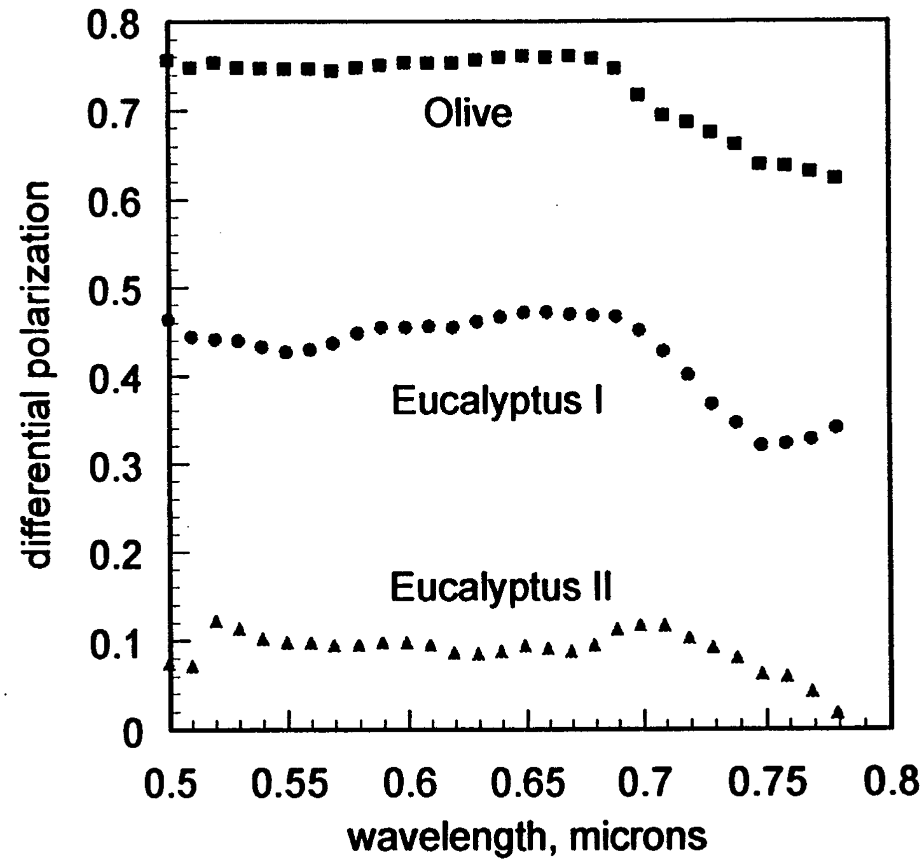
With polarization parallel (||) and perpendicular (⊥) to incident plane

REFLECTIVE AND DERIVATIVE SPECTRA OF EUCALYPTUS LEAF AT SPECULAR ANGLE





POLARIZATION SPECTRA OF GREEN LEAVES



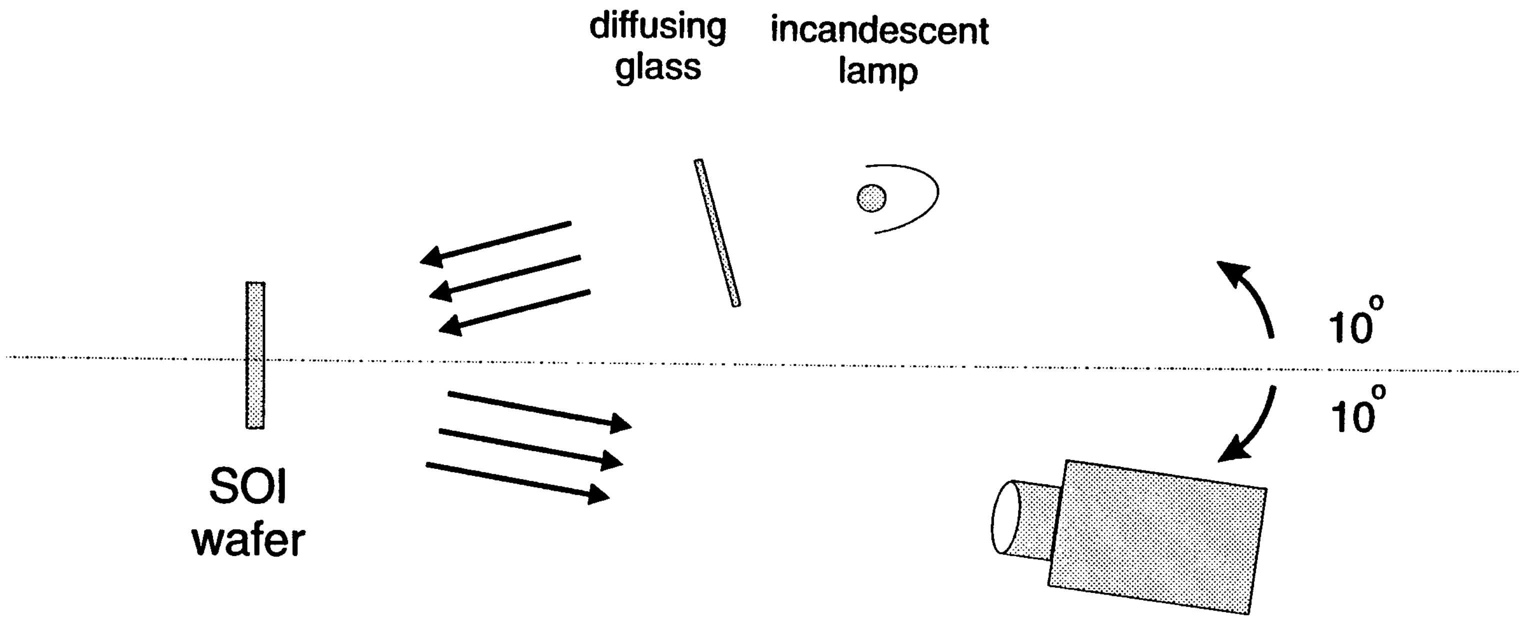
differential polarization = $(I_{\perp} - I_{\parallel}) / (I_{\perp} + I_{\parallel})$

phase angle = 125 degrees

CHARACTERIZATION OF SILICON-ON-SILICON USING AOTF-PHI

Silicon-On-Silicon (SOS)
is
A most promising material
of silicon-on-insulators,
important for future advanced VLSI.

EXPERIMENTAL SETUP



Spatial Resolution per pixel:
about100 microns

WHITE-LIGHT INTERFERENCE PATTERN
as a function of wavelength
at two orthogonal polarizations

LJC/10/94

JPL

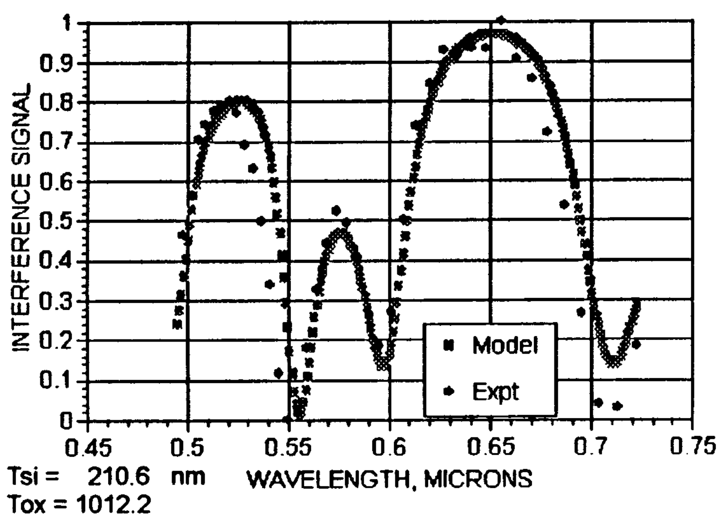
WHITE-LIGHT INTERFERENCE IMAGE CUBE

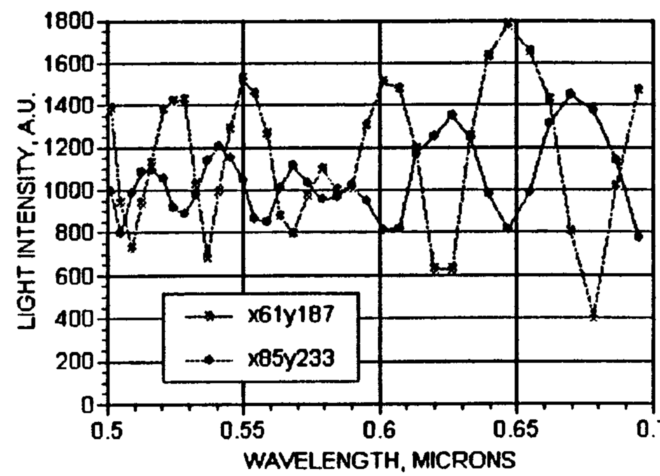
↓

interference spectrum ⟶ **layer thickness maps**
deviations from model

interference amplitude reduction and DC component ⟶ **surface/interface roughness**

polarization images ⟶ **surface/interface topographies**
abnormal interface structures





LJC/9/94

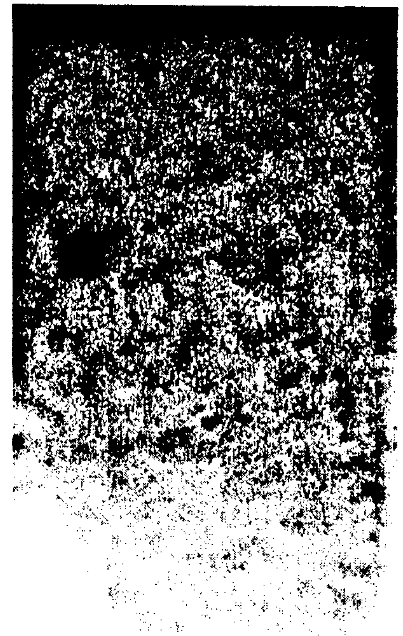
JPL

Interference Images

0.550 μ

0.574 μ

Interference Amplitude Map



perpendicular

parallel

to incident plane

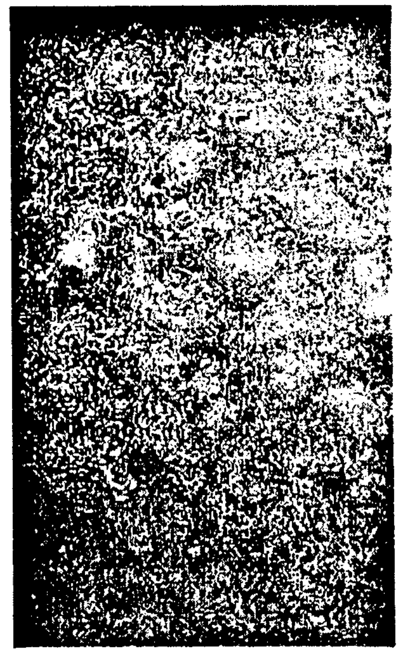
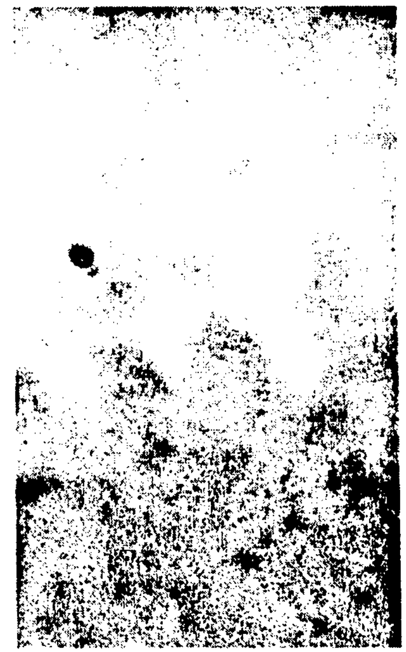
Defined as
(Imax - Imin)

SEH/AcuThin SOI Sample

LJC/9/94

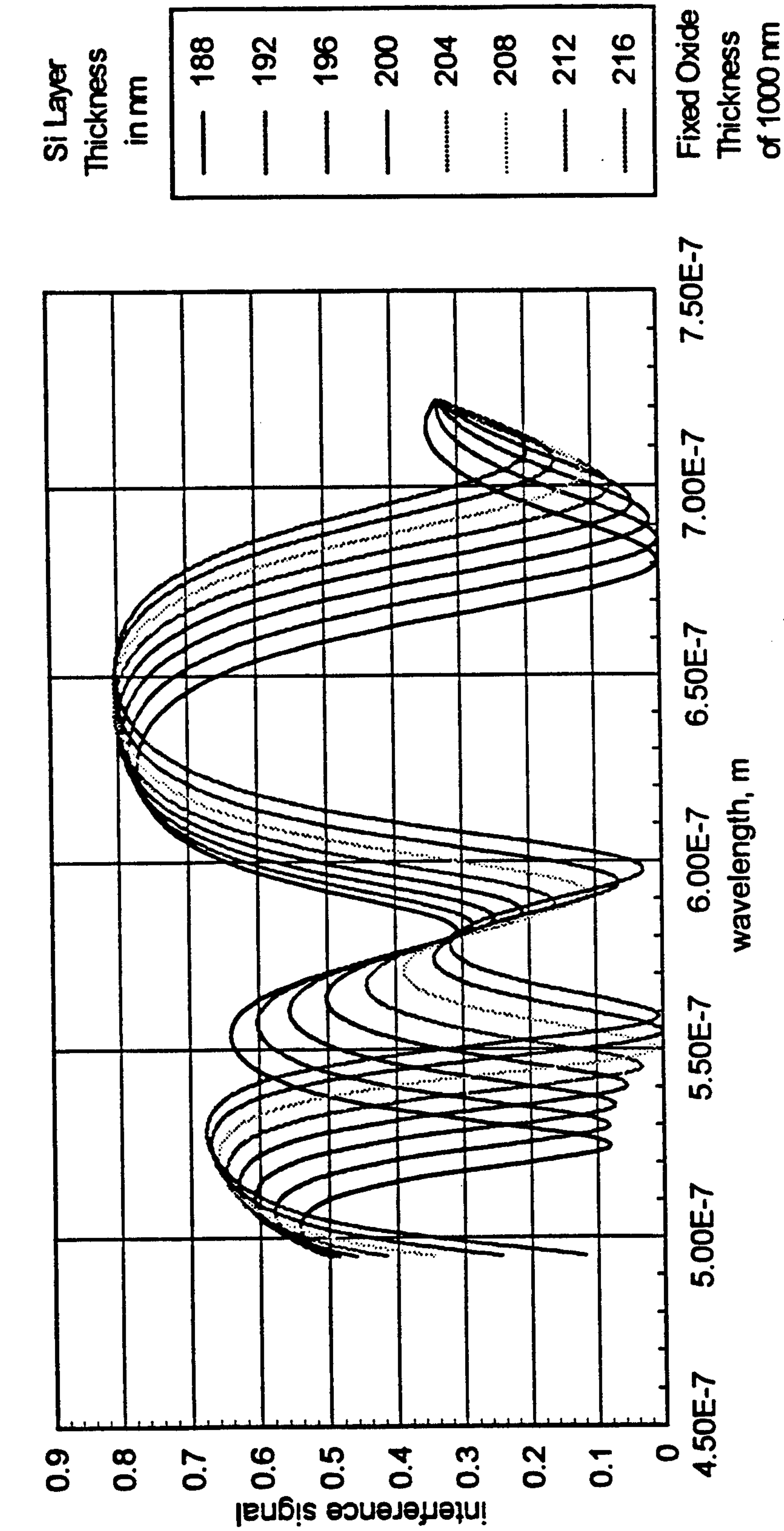
JPL

MAPS OF SILICON AND OXIDE LAYER THICKNESS WITH CORRELATION FACTOR BETWEEN MODEL AND MEASURED SPECTRA

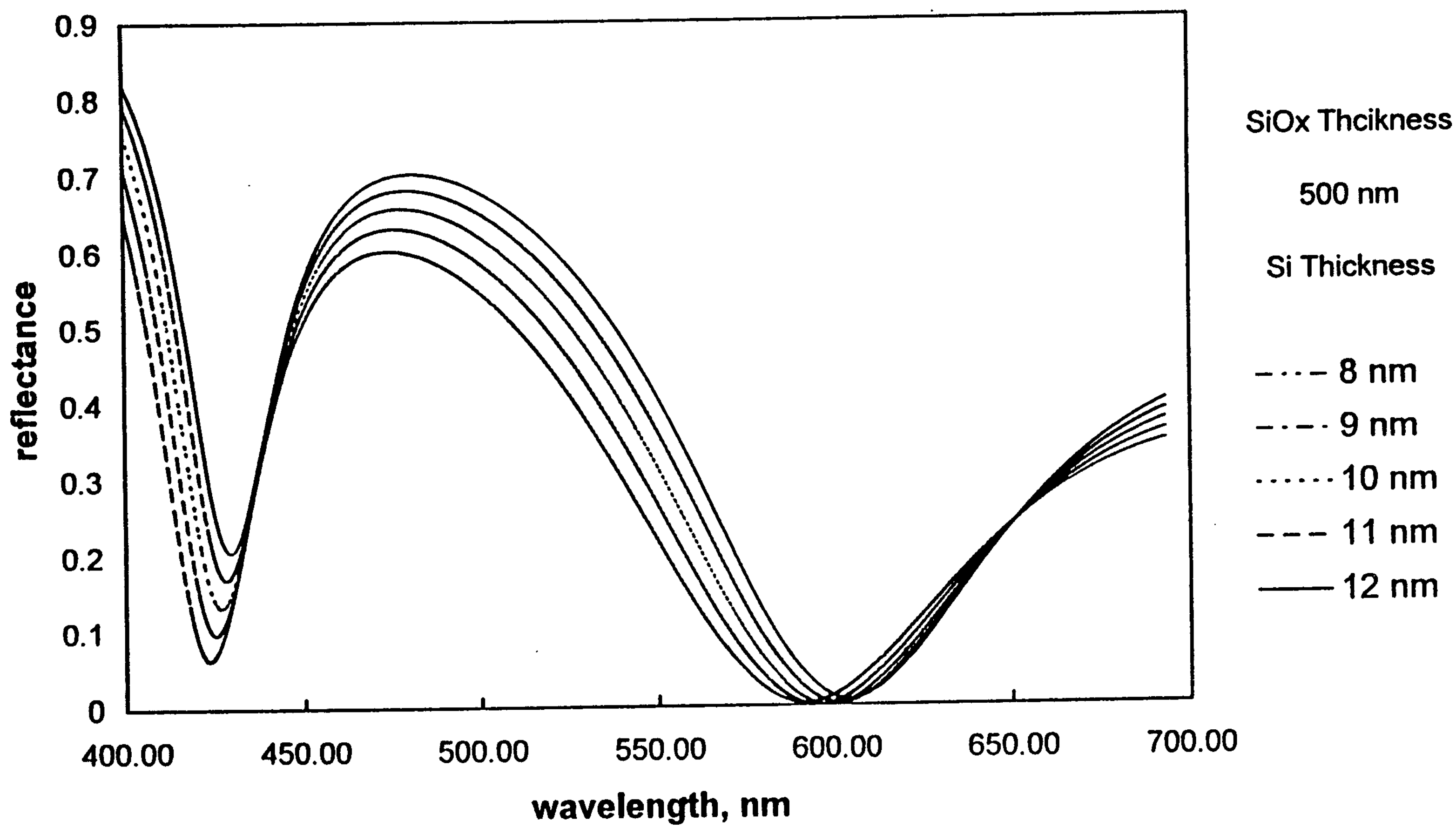
	Silicon	Oxide	Correlation
			
Mean	206.4 nm	1014.7 nm	0.9821
Stdev	5.90 nm (2.96%)	3.48 nm (0.34%)	0.0046 (0.46%)

SEH/AcuThin SOI Sample

LJC/9/94



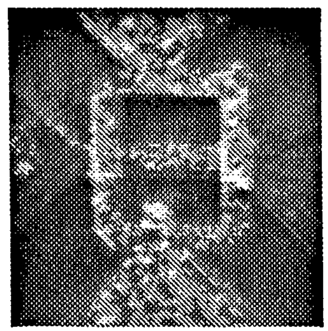
interference signal
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
4.50E-7
5.00E-7
5.50E-7
6.00E-7
6.50E-7
7.00E-7
7.50E-7
wavelength, m
Si Layer Thickness in nm
188
192
196
200
204
208
212
216
Fixed Oxide Thickness of 1000 nm



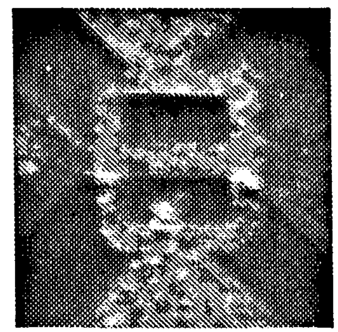
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
reflectance
400.00
450.00
500.00
550.00
600.00
650.00
700.00
wavelength, nm
SiOx Thcikness
500 nm
Si Thickness
8 nm
9 nm
10 nm
11 nm
12 nm

JPL

MICROSCOPIC AOTF IMAGES OF AN INDIVIDUAL FET TEST DEVICE ON A VLSI WAFER



vertical polarization



horizontal polarization

AT 0.685 MICRONS

JPL

1.2-2.4 Micron Infrared Airborne Prototype System (Under Development)

- Compact folded optical configuration.
- Simultaneous two-polarization imaging side-by-side on one Rockwell cooled focal plane array of HgCdTe. (a low-cost approach).
- Through-the-system video tracking.
- Real-time instrument capable of collecting an image cube data in Seconds.
- TeO_2 AOTF designed and manufactured by Aurora.

ljc

Important Spectral Features in 1.2-2.4 micron.

- **Two major absorption bands due to H_2O and CO_2 in the atmosphere.**

  No useful solar are available at the wavelength of these two band.

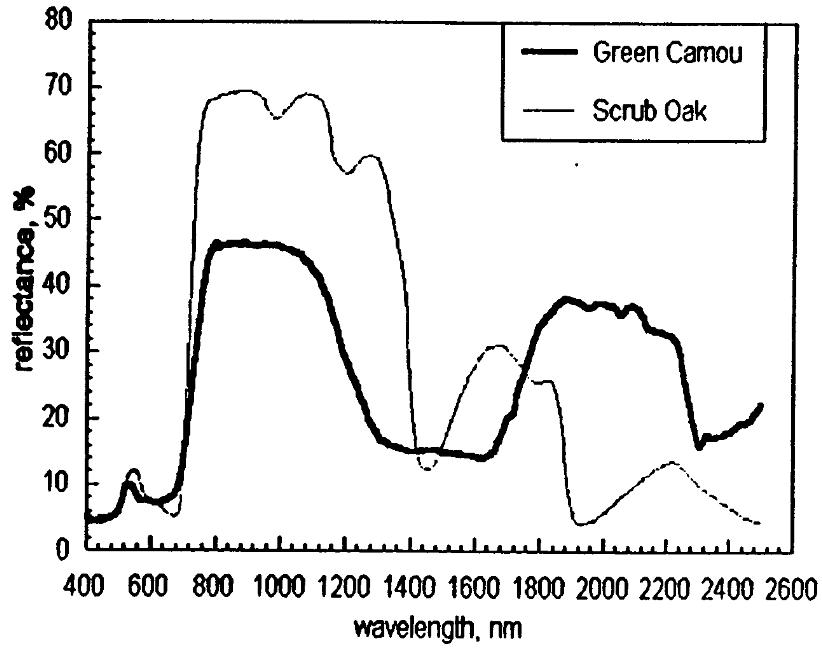
- **Characteristic Spectral Signature of Man-Made Materials**

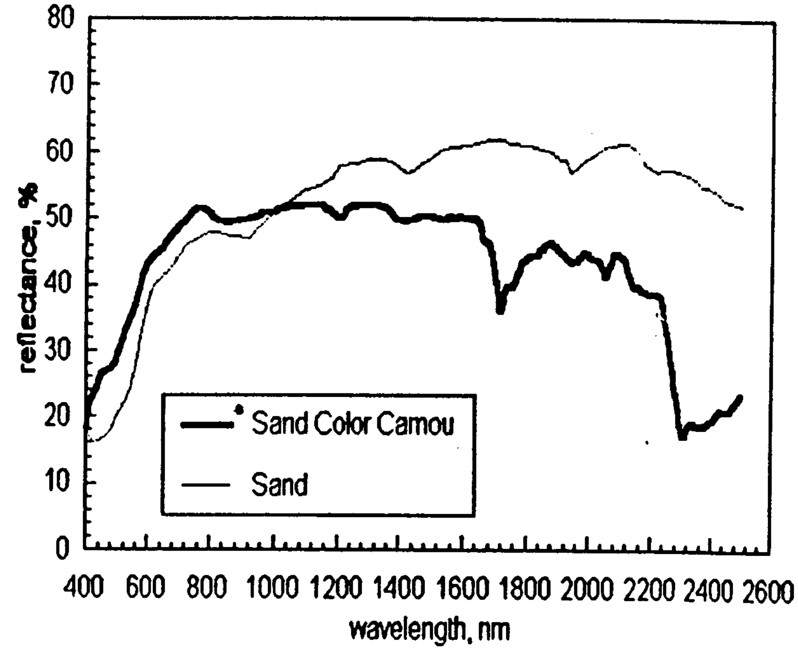
  Textures and paints are often made of synthetic materials, originally from petroleum products. These products often have characteristic absorption bands at 1.7 and 2.3 microns. This also applies to camouflaged cloths and painted surface. Consequently, the capability to detect these bands will provide an effective classification process for military applications

ljc

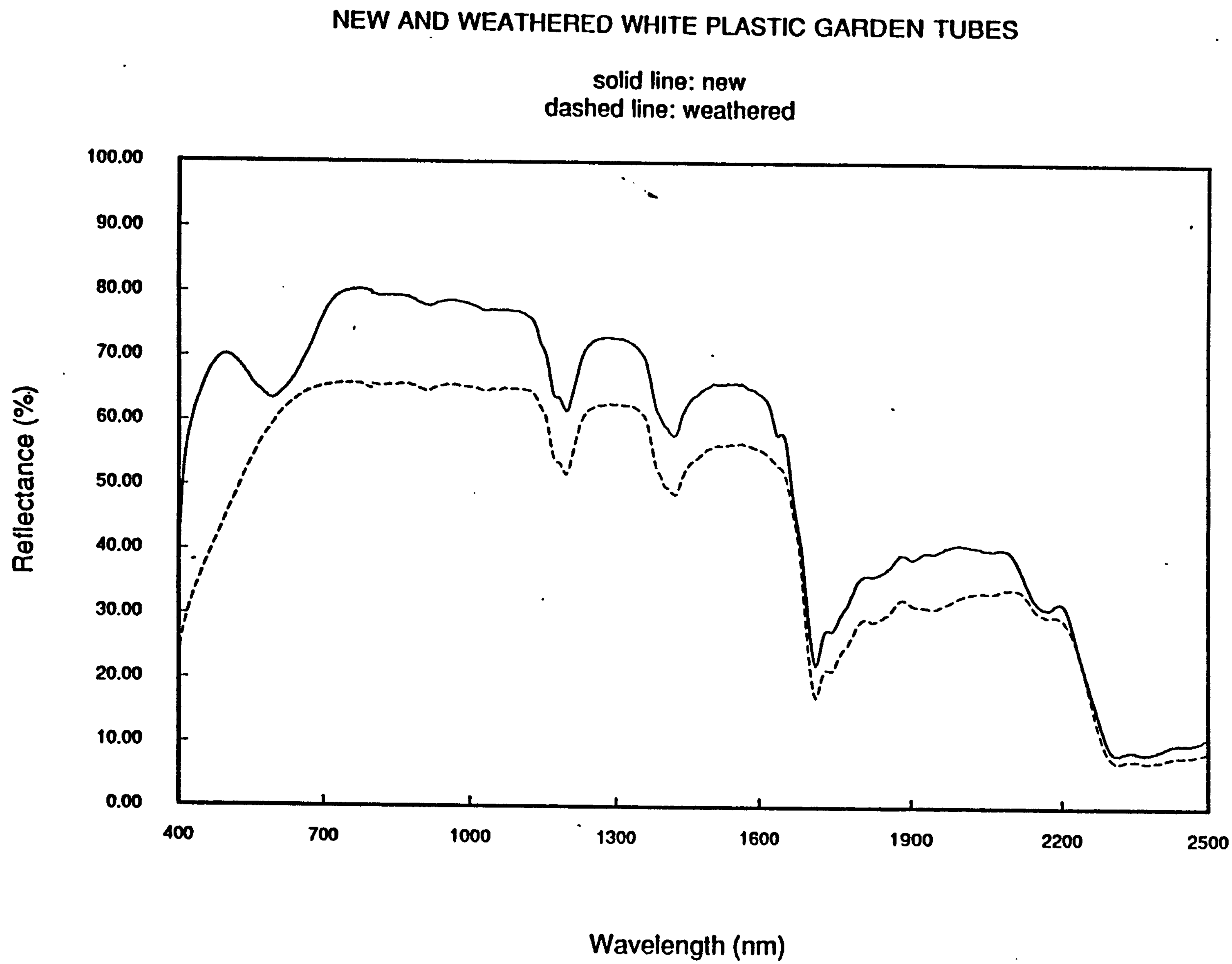
JPL

Comparison of Camouflaged Net and Natural Materials in Reflectance Spectrum





LJC/5/95



Tue Oct 1 10:27:20 1991

Distribution

Admnstr
Defns Techl Info Ctr
Attn DTIC-OCP
8725 John J Kingman Rd Ste 0944
FT Belvoir VA 22060-6218

ERDEC
Attn SCBRD-RTE-E3549 J O Jensen
Attn CAPT A C Samuels
APGEA Edgewood MD 21010-5423

Hdqtrs Dept of the Army
Attn DAMO-FDQ MAJ M McGonagle
Attn DAMO-FDQ D Schmidt
400 Army Pentagon
Washington DC 20310-0460

Night Vsn Dirctrt
Attn L J Mizerka
10221 Burbeck Rd Ste 430
FT Belvoir VA 22060-5806

US Military Academy
Dept of Mathematical Sci
Attn MAJ D Engen
West Point NY 10996

Nav Rsrch Lab
Attn Code 5603 I Aggarwall
Attn Code 5603 D Daganias
Washington DC 20375

Oak Ridge Natl Lab
Attn T Vo-Dinh
PO Box 2008 MS 6101
Oak Ridge TN 37831-6101

Case Western Reserve Univ
Dept of Electrl Engrg
Attn D A Smith
Cleveland OH 44106

Instite of Crystallography
Attn Y Pisarevsky
Moscow
Russia

Marquette Univ Dept of Chemistry
Attn C Tran
PO Box 1881
Milwaukee WI 53201

Moscow State Univ Dept of Physics
Attn V Voloshinov
Moscow 119899
Russia

ST Petersburg State Academy of
Aerospace Instrmntn
Attn V V Kludzin
Attn V V Molotok
67 B Morskaya Str
ST Petersburg 100000

Univ of California
Dept of Elect & Computer Engrg
Attn C S Tsai
Engeering Gateway Bldg
Irvine CA 92697

Univ of Pittsburgh
Chevron Science Center
Attn J Turner
Room 314
Pittsburgh PA 15260

J Goodell
1201 Southview Rd
Baltimore MD 21218

Advncd Materials Corp
Attn C J Thong
Attn M Uschak
Attn S G Sankar
Attn S Simizu
700 Technology Dr Ste 3311
Pittsburgh PA 15230-2950

Aurora Assoc
Attn I C Chang
3350 Scott Blvd B-20
Santa Clara CA 95054

Distribution

Brimrose Corp of America
Attn S Trivedi
Attn V Pelekhaty
Attn W J Danley
5020 Campbell Blvd
Baltimore MD 21236

Brookhaven Natl Lab
Attn C L Chen
Bldg 197C DAT/SSN
Upton NY 11973

Brookhaven Natl Lab
Attn D Heglund
Box 5000 Bldg 701
Upton NY 11973

Carnegie Mellion Rsrch Instit
Attn M Gottlieb
Attn B Kaminsky
Attn L J Denes
700 Technology Dr PO Box 2950
Pittsburgh PA 15230-2950

Central Design Bureau for Unique Instrmnt
Attn V I Pustovoit
Moscow 117342
Russia

Jet Propulsion Lab
Attn M/S 300-329 L-J Cheng
4800 Oak Grove Dr
Pasaolena CA 91109

Massachusetts Instit of Techlgy
Attn Piotr Becla
Room 13-4111
Cambridge MA 02139

Natl Instit of Health
Attn E N Lewis
Bldg 5 Room B1-38
Bethesda MD 20892

Neos Technologies Inc
Attn E Young
4300C Fortune Pl
Melbourne FL 32904

Photonic Sys Inc
Attn J A Carter III
Attn D R Pape
1800 Penn Stret Ste 6
Melbourne FL 984-8181

Army Rsrch Lab
Attn AMSRL-PS-ED J S Himmel
FT Monmouth NJ 07703-5601

US Army Rsrch Lab
Attn AMSRL-WM-PC A W Miziolek
Attn AMSRL-WT-PC E D Lancaster
Attn AMSRL-WT-PC K L McNesby
Aberdeen Proving Ground MD 21005-5066

US Army Rsrch Lab
Attn AMSRL-CI-LL Tech Lib (3 copies)
Attn AMSRL-CS-AL-TA Mail & Records Mgmt
Attn AMSRL-CS-AL-TP Techl Pub (3 copies)
Attn AMSRL-IS-EE J B Gillespie
Attn AMSRL-SE-SS C DeLuca
Attn AMSRL-SE-EO N Fell
Attn AMSRL-SE-E J Pellegrino
Attn AMSRL-SE-EO A Filipov
Attn AMSRL-SE-EO N Gupta (5 copies)
Attn AMSRL-SE-ES D McCarthy
Adelphi MD 20783-1197

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	February 1997	Final, from Jan 1996 to Jan 1997

4. TITLE AND SUBTITLE
Viewgraph Supplement to the Proceeding of 1st ARL AOTF Workshop

5. FUNDING NUMBERS
PE: 65709A

6. AUTHOR(S)
Neelam Gupta, Editor

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
Attn: AMSRL-SE-EO
2800 Powder Mill Road
Adelphi, MD 20783-1197

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-SR-54-S

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
2800 Powder Mill Road
Adelphi, MD 20783-1197

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
AMS Code: P665709.650
ARL Proj: AN7NEGAA

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Acousto-optic tunable-filter (AOTF) technology is a recent development that offers potential for rapid, frequency-agile tuning over a large optical wavelength range. An AOTF is an electronically tunable phase grating set up in an anisotropic crystal by the propagation of an ultrasonic wave in the crystal. Such filters have many attractive features, such as small size, lightweight, computer controlled operation, large optical wavelength range of operation, and no moving parts; and their operation can be made ultrasensitive by the use of advanced signal processing algorithms. These filters are being used in many applications such as the design of new spectroscopic instruments, remote detection and monitoring of chemicals, optical communication networks, tuning of laser cavities, etc.

14. SUBJECT TERMS
AOTF, spectrometer, chemical sensing, biological sensing, imaging

15. NUMBER OF PAGES
181

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102